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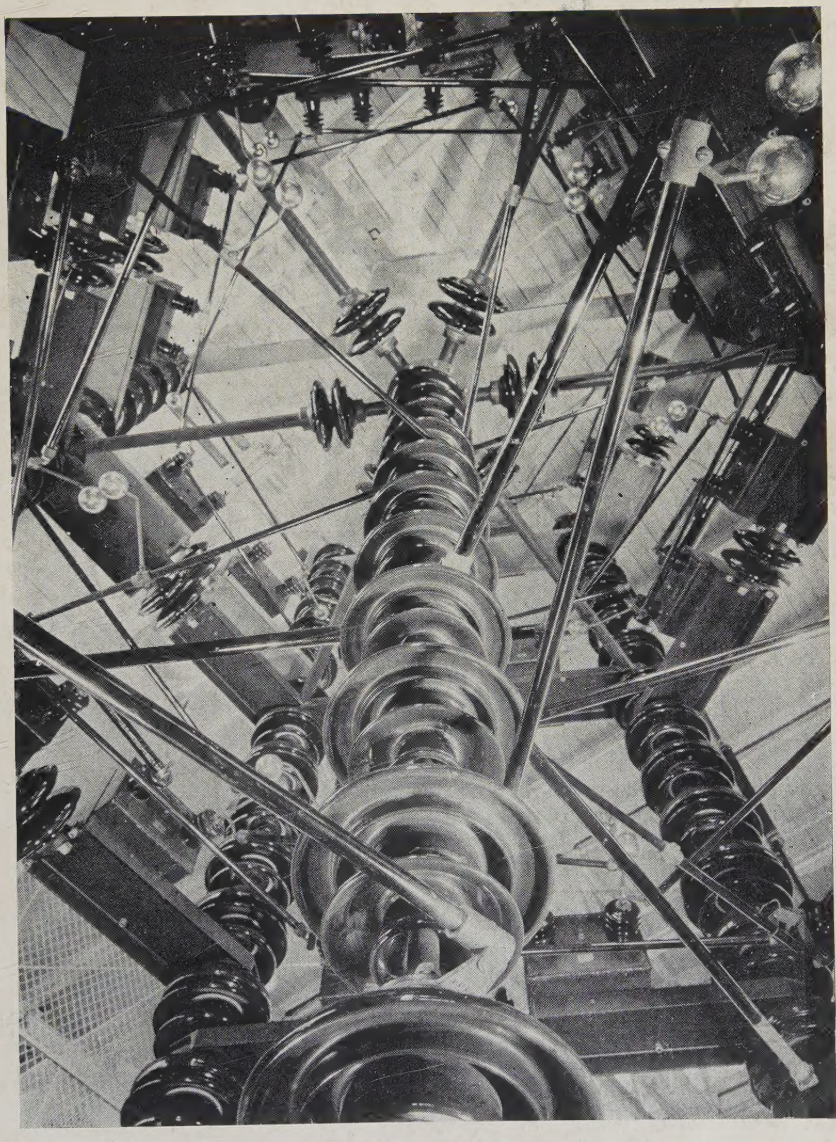

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Front Cover

Looking up through the interior of the new 3,000-kv impulse generator with helical mounting at the Ohio Brass Company's high voltage testing laboratory, Barberton, Ohio. (See description in ELEC. ENGG., v. 53, 1934, p. 1255–9.)

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Fundamental Electrical Properties of Mercury Vapor and Monatomic Gases

By ALBERT W. HULL, Member Am. Phys. Soc.
General Electric Co., Schenectady, N. Y.

Electrical properties of mercury vapor and monatomic gases are discussed from a theoretical standpoint in this article. In the first part of the article, the author discusses briefly the elementary processes of excitation and ionization of atoms upon which the electrical properties of gases depend. With this insight into the fundamental processes as a background, the author discusses in Part II the electrical conductivity of gases under various conditions. This is the eleventh in a series of special articles prepared under sponsorship of the A.I.E.E. committee on education.

GASES in their normal states are electrically neutral. A discussion of the electrical properties of gases therefore must deal with abnormal states. The 2 abnormal states of atoms are *excitation* and *ionization*.

When an electron collides with an atom, one of 4 things may happen: nothing at all, deflection, excitation, or ionization. In the inert gases, nothing at all happens at low electron energy, less than about one volt. (Electron energies are measured in "equivalent volts" or "electron volts"—energy = eV = charge of electron $\times$ accelerating voltage—and generally are given, for brevity, in volts.) The electron passes through the solar system of the atom with no loss of energy and only slight probability of deflection. This transparency to slow electrons is a unique property of the inert gases.[1] It usually is expressed in terms of the small "cross section" that the atom presents to a colliding electron, as shown in Fig. 1. The cross sections to be expected from the kinetic theory of gases are shown at the right.

With increasing electron velocity, the "effective cross section" of the atoms becomes larger, several times as large as the kinetic theory value; this means that collisions are very frequent. However, these are deflecting collisions only, involving no loss of energy,* provided the electron velocity is less than a critical value. This is intelligible on the basis, now well established, that atoms can exist only in discrete states. The atom cannot take energy from an electron unless it can do something with the energy, *viz.*, store it in some form; and an atom cannot store energy unless there is enough to raise it to its next higher state, namely, to one of the excited states, or the ionization state. For the inert gases the lowest of these states requires more than 10 volts energy (see Table I).

The picture changes entirely when the electron energy reaches a value equal to the first excitation potential.[2] Collision then results in a transfer of energy from the electron to the atom, which now becomes abnormal or excited. The excited atom usually radiates its energy, as light, within a period 10^{-8} sec. This light, however, is highly absorbable by other atoms of the same kind, exciting them in turn, and so is passed on from atom to atom until it reaches the confines of the gas envelope and is radiated into space or absorbed. A state of excitation thus persists in the gas for an appreciable time; and this time is increased further by a mechanism known as a "metastable" condition, which results when an excited atom loses a small amount of its energy by a collision of some kind and becomes thereby incapable of radiating light. Such atoms remain in the excited state until they lose their energy by collisions with other atoms or the walls of the container, or until they receive additional energy from an electron, by another collision, sufficient to ionize them. This latter process is important for arcs. The probability of a second electron collision is proportional to the number of excited atoms and the number of exciting electrons, hence to the square of the current. Most of the ionization in low pressure arcs is of this multistage or cumulative type.

If the energy of the impinging electron is still higher, it reaches in turn the other excitation potentials of the atom, of which there are several, and finally the ionizing potential. At this potential the energy is sufficient to cause the ejection of an electron from the atom, yielding a positively charged ion and 2 slow electrons, *viz.*, the original electron, which has lost its energy in the collision, and the one taken from the ion.

The probability that a collision will result in excitation is known only approximately. From the value zero, for electron energies less than the excitation potential, it jumps to a maximum when the energy is just equal to the excitation potential, decreasing rapidly as it exceeds this value. The best measurements available[3] give a maximum probability between 0.001 and 0.003 per collision at a voltage only slightly higher than the excitation potential, falling to $^1/_4$ the maximum at 0.50 volt above the critical value.

The probability that a collision will result in ionization is known quite accurately.[4] It is zero for

1. For all numbered references see list at end of article.

* There is, of course, the slight loss to be expected on the basis of classical mechanics, *viz.*, a fraction $2m/M$ per collision on the average. This amounts to approximately 3 parts in 10,000 and 5 parts in 1,000,000 per collision with helium and mercury atoms, respectively.

energies less than the ionizing potential, but, unlike excitation, it is very small *at* the ionizing potential and increases gradually and uniformly with further increase of energy. It is very nearly proportional to the excess of energy above the ionizing potential for energies up to twice the ionizing potential, reaches a maximum at about 10 times the ionizing potential, and is inversely proportional to voltage at high voltages. These probabilities are given in Table I, together with the ionization potentials and the excitation potentials. They are shown graphically in Fig. 2 for voltages up to 1,000.

Besides excitation and ionization, 4 other elementary processes are important to the electrical

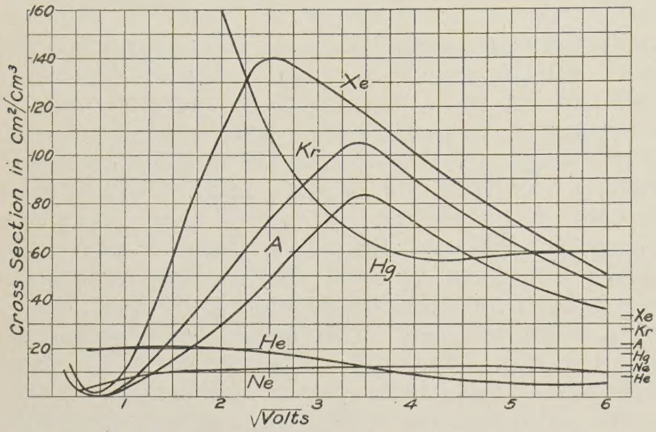


Fig. 1. Effective cross section of gases for slow electrons

Ordinates represent the total cross section of the atoms in 1 cu cm of gas at 1 mm (of mercury) pressure and 0 deg C. This is equal to the number of collisions an electron will make in traveling 1 cm through the gas. (From data by Ramsauer and Kollath)

behavior of atoms. The first is the exchange of charge (Umladung) which occurs when an ion collides with an atom.[5] The ion takes an electron from the atom and goes on its way as a fast moving atom, leaving a slow ion behind. It is to be noted that no free electrons are produced in this process. This exchange appears to be a very important process, occurring, for argon ions in argon, more than 4 times as frequently as the total number of calculated collisions; this means that the ion is able to grab an electron from an atom when it passes within a distance twice as great as would constitute a collision between atoms according to classical theory.

The next (fourth) process is electron emission caused by the impact of ions or excited atoms on

Table II—Ionization Potentials of Gases for Positive Ion Impact (From Beeck and Mouzon)

Gas	Ionization Potential in Volts				
	Li^+	Na^+	K^+	Rb^+	Cs^+
Ne	307	175	320	420	437
A	100	105	95	180	365
Kr	420	400	80	100	143
Xe	250	360	120	145	105

metals.[6] This process is responsible for the maintenance of electron emission at the cathode in the glow discharge. The probability of impact emission is greater the higher the energy, both kinetic and potential, of the impinging article, thus increasing with velocity of the ions and with the ionization and excitation potentials. The values of this probability, as far as they are known,[6] are given in Fig. 3.

Ionization of atoms by positive ion impact[7] is a much less probable process than those that have been discussed, yet it is believed to be important, especially at high voltages. This process also is found to set in at definite "ionization potentials" (Table II), though the theoretical interpretation of these potentials is not yet clear. The probability that an impact will result in ionization is the greater, and the ionization potential the lower, the nearer alike the ion and atom. These probabilities, as far as they are known, are shown in Fig. 4. It should be noted that they are only a few per cent of the corresponding probabilities for electron impacts. They increase with voltage, without reaching a maximum. That a maximum probably exists, at much higher voltages, is indicated by the fact that ionization by doubly charged helium atoms or "alpha particles" is inversely proportional to speed.

A fifth process, the ionization of atoms by fast moving atoms, has been discovered[8] recently and

Table I—Values of Ionizing Potential, $\bar{V}_i$, First Critical Potential $\bar{V}_c$, Mean Free Path of Electron λ, and Probability of Ionization $P(\bar{V})$.† (Data From P. T. Smith)

Gas	$\bar{V}i$	$\bar{V}c$	λ (cm) (at p = 1 mm & 0°C)	$P_{(20)}$	$P_{(30)}$	$P_{(50)}$	$P_{(100)}$	$P_{(300)}$	$P_{(1,000)}$	$P_{(3,000)}$	$P_{(10,000)}$
He	24.48	19.73	0.1203	0.00	0.25	0.86	1.25	0.97	0.49	0.183	0.056
Ne	21.47	16.60	0.0753	0.00	0.48	1.47	2.66	2.71	1.29	0.57	
A	15.69	11.57	0.0431	3.07	8.4	11.7	12.9	8.6	3.66	1.53	
Hg	10.39	4.66	0.0142*	8.1*	13.7*	17.9*	19.3*	14.6*	7.30*	3.35*	1.03*
Kr	13.3	9.9									
Xe	11.5	8.3									

† $P(\bar{V})$ = probability that an electron with $\bar{V}$ volts energy will ionize an atom in moving 1 cm through the gas at 1 mm pressure and 0 deg C.

*Since the pressure of mercury vapor at 0 deg C is only 0.000185 mm (of mercury), these values are to be interpreted as the values per millimeter pressure, and used only at low pressures. For higher pressures correction must be made for the actual temperature T of the vapor, by multiplying by $\sqrt{T/273}$ the values of λ given in the table, and dividing the values of P by the same factor

appears to be of great importance. It is believed to be much more probable, per collision, than ionization by ions, with which it intimately is connected through the exchange process discussed previously. Numerical values of this probability have not yet been obtained, since it is a matter of some difficulty to measure the number of neutral atoms in the beam; but it is known to be a maximum when the 2 atoms are of the same kind. This process is probably effective in thermal ionization, such as exists in high pressure arcs. In view of the high probability of the exchange process, high speed atoms must be as numerous as ions in all gaseous discharges; their ionizing power is therefore of great importance.

A sixth process, ionization of an atom by contact with an excited atom, is a probable and important event in mixed gases. The excitation energy obviously must be sufficient for the purpose, which means that the excitation potential of the excited atom must exceed the ionization potential of the atom to be ionized. The probability of the process appears to be maximum when the excess of energy is small. This process is important in preventing loss of cathode material in certain low pressure arcs (see following discussion).

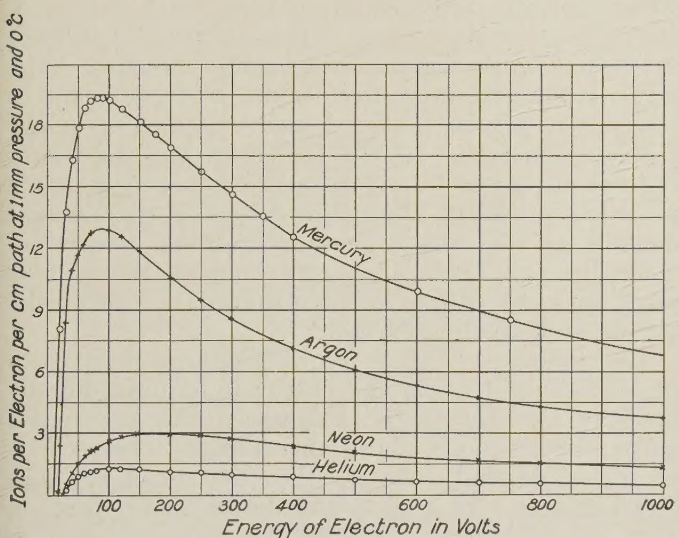


Fig. 2. Probability of ionization by electrons

Ordinates are the probabilities that an electron moving with energy V will produce 1 ion in moving 1 cm through a gas of the given kind at 1 mm (of mercury) pressure and 0 deg C. (See note, Table I, for mercury.) The probabilities for other pressures and temperatures are proportional to the number of collisions (for low pressures), and hence are directly proportional to pressure and inversely as the square root of temperature. (From data by P. T. Smith)

Part II—Electrical Conductivity of Gases

"Natural" Conductivity

An un-ionized gas between non-electron-emitting electrodes is a perfect nonconductor. This condition never can be quite realized, because cosmic rays and radioactivity of the earth cause a slight ionization of the air and a slight electron emission from the electrodes, which cannot be avoided. The "natural" ionization in air from these causes averages about 2 ions per cubic centimeter per second at atmospheric pressure at sea level, and nearly 100 times as many at the highest altitude at which cosmic ray measurements have been made. The saturation current between electrodes one centimeter square and one centimeter apart in air, due to this cause, is 3×10^{-19} amp and 3×10^{-17} amp, respectively. For argon at the same pressure these currents are approximately 40 times greater. Hence argon is adapted for use in measuring the intensity of X rays and cosmic rays. The "ionization chamber" carried by Commander Settle and Major Fordney on their November 1933, stratosphere flight contained argon at a pressure of 2.4 atmospheres.

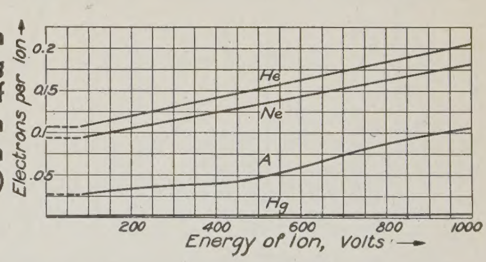
Conductivity With Electron Emitting Cathode; "Transmissivity" of Electrons by Monatomic Gases

Conductivity is of a higher order, even without ionization, when the cathode emits electrons. The atoms of the inert gases present such a small "effective cross section" to slow electrons (see Fig. 1) that they offer little resistance; and the deflecting collisions, which become more numerous with increasing velocity, merely change the direction but not the speed of the electrons. Thus a photoelectric cell containing argon will readily conduct currents ranging from a microampere to a milliampere, when suitably illuminated, at voltages too low to ionize the gas. The current in this case is limited either by electron space charge or photoelectric emission, whichever gives the smaller value.

Townsend Discharge; Amplification of Current by Gas Ionization

A third kind of conductivity, of a higher magnitude still, is obtained when the voltage is high enough so that ionization can take place.[10] This has 2 effects. In the first place, the number of electrons

Fig. 3. Electron emission resulting from impact of postive ions on nickel. (From data by Penning)



is doubled at each ionizing impact. If n_0 is the number of electrons leaving the cathode, *e. g.*, photoelectrons in a photo-electric cell, and if the electric field and pressure are such that the probability of ionization per centimeter path is α (see Table I), then the number of new electrons produced in a distance dx will be $dn = n\alpha dx$, and the number reaching an anode d centimeters distant will be $n_0 e^{\alpha d}$. The current thus will be amplified $e^{\alpha d}$ times. At low

gas pressures, of the order of 0.001 mm of mercury, the values of α can be found from Table I and Fig. 2, taking for $\overline{V}$ the voltage per mean free path (voltage gradient times mean free path) and multiplying by the pressure in millimeters of mercury. At high pressures, *e. g.*, 10 mm or more, and moderate voltages, the number of collisions is so large that an electron has ample opportunity to ionize before its energy rises more than a few per cent above the ionizing potential. Hence α is the number of ionizing potentials per centimeter (voltage gradient divided by ionizing potential). A value slightly higher than the ionizing potential obviously must be used in this calculation, in order to allow for a few impacts after reaching the ionizing potential, and for some loss of energy in excitation.

The second effect of ionization is that the positive ions neutralize part of the space charge of the electrons and allow the amplified currents to flow with lower voltage. This leads to distortion of the electric field, and, when carried beyond a certain point, to instability and a self-sustaining discharge.

This type of "amplification by ionization" is in general use in photo-electric tubes where maximum sensitivity is desired. Stable amplifications of 100-fold easily are obtained with small current densities. For large current densities, it is generally difficult to obtain more than 10-fold stable amplification.

Glow Discharge; Sparks

A fourth stage is reached when the gas amplification exceeds the probability that an ion striking the cathode will produce an electron by its impact. The discharge then is self-maintained. A single electron produced near the cathode by cosmic radiation or other means will be amplified $e^{\alpha d}$ times before reaching the anode, and these $e^{\alpha d}$ ions, when

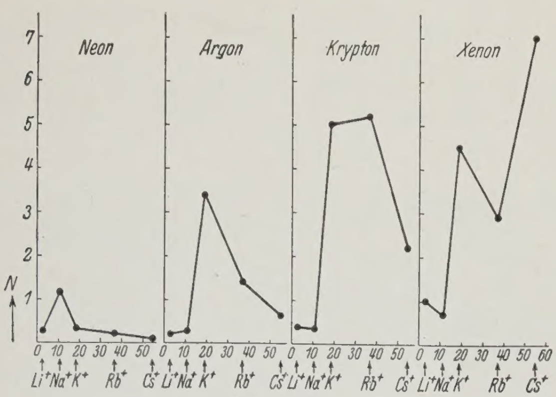


Fig. 4. Ionization of atoms by positive ion impact (Beeck and Mouzon)

they reach the cathode, will produce more than one electron; hence, the current gradually will build up to a value limited only by space charge or circuit resistance. This discharge is known as a "glow discharge." The normal glow discharge has the unique characteristic that its current density at the cathode is fixed for a given gas pressure. As the current

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increases, the discharge utilizes more and more of the cathode surface, the voltage remaining constant; only when the cathode is entirely covered with glow does the voltage begin to rise. This property has been used for voltage regulation for small currents. The current per unit area of cathode is proportional to the square of the pressure, and depends upon the cathode material. Table III gives the values of the current density for the inert gases and mercury at 1-mm pressure. From these values the current density at any other pressure can be calculated. The values in Table III may be used without great error for most other electrode materials, except the alkalis and alkaline earths.

The voltage at which glow discharge begins depends for a given gas and electrode material on the pressure and the distance between the electrodes, and is easily shown, both theoretically and experimentally, depend only on the product of pressure and distance. In Fig. 5 are shown these sparking

Table III—Normal Current Density in Glow Discharge at Pressure of 1 Mm at 18 Deg C (Guntherschulze)

Gas	Cathode Material	Current Density, Ma per Sq Cm
Hg	Iron	0.010
A	Platinum	0.140
Ne	Platinum	0.018
He	Platinum	0.011

potentials for the gases under consideration, as a function of this product.[11]

The potentials at which glow discharge starts have been referred to as "sparking potentials." The glow discharge and the spark differ only in the final stage, namely, in whether the discharge remains limited by the combination of positive-ion space charge and the number of electrons produced by impact of these ions on the cathode, or becomes arc-like. Arcs will be discussed later. Both glow discharges and arcs are observed at all pressures from 1 mm of mercury to atmospheric. As far as the starting phenomena are concerned, they may be considered identical.

The most important characteristic of the starting of a spark or glow discharge, next to the sparking potential, is the time lag—the time that elapses

after the voltage is applied before the current reaches its full value. There are 2 kinds of time lag in all sparks. The first is the delay in waiting for the first electron. In pure gases, free from dust, this may be a considerable fraction of a second, or even many seconds if the distance be small or the pressure low. Since it is a question of waiting for the first cosmic ray or radioactive product to enter the space between

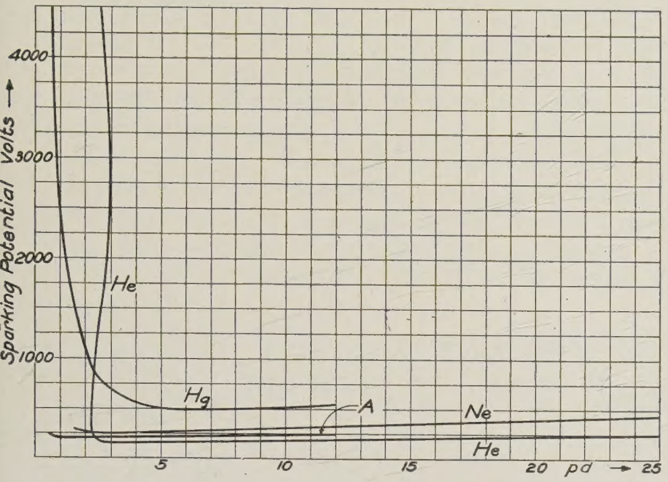

Fig. 5. Sparking potentials in gases, with iron or nickel electrodes, as function of the product, pd, of pressure and distance

Pressure, p, is in millimeters of mercury; distance, d, in centimeters. (From data by Penning for helium and neon, Ayres for argon, Smede for mercury)

the electrodes, the delay should be a matter of pure probability, and this has been demonstrated amply by experiment. It can be eliminated by illuminating the cathode with ultra-violet light. A photoelectric emission of only 0.001 μamp (10^{-9} amp) means 6 billion (6×10^9) electrons per second, and thus the average time lag between electrons is only $^1/_{6,000}$ μsec. In the case of a hot thermionic cathode, this kind of time lag is absent.

The second kind of time lag is the time required for the multiplication process. At low gas pressures this "building-up" time is from 1 to 100 μsec. It requires some motion on the part of ions, and hence is longer the heavier the atoms and the greater the distance from anode to cathode. The values for cold cathodes are longer than for hot cathodes, but generally are obscured by the much longer lag of the first kind, which has a mean value of the order of 10^{-3} sec at 1-mm pressure.

At high pressures the multiplication is effected by distortion of the electric field by the ions that are formed by electron impact without any motion on the part of the ions. It therefore can be very rapid, since the time required for electrons to cross the space is between 10^{-7} and 10^{-8} sec for practical spark lengths. The mechanism is as follows: Assume an electron to leave the cathode in a field slightly above the sparking potential. It will be multiplied along its path, producing more and more ions as the anode is approached. When all the electrons thus produced have reached the anode, there will be left in the space near the anode enough ions to increase appreciably the electric field in the rest of the space. The ions may be considered as stationary because of their sluggishness, and as building out the positive anode in the direction of the cathode. The second electron leaving the cathode therefore will travel in a stronger field, and will produce more ions than the first, thus making a still stronger field for the third, etc. Each stage in this process requires less than $^1/_{10}$ μsec. The multiplication per stage is greater the greater the spark length; hence, at high pressures, this type of time lag decreases with increasing distance between electrodes, which is opposite to the behavior at low pressures. Theory and experiment show that, for sparks of the order of 1 cm or more, at atmospheric pressure, the time required for this building up process is $^1/_{10}$ μsec or less. A typical oscillogram of a spark in air at atmospheric pressure is shown in Fig. 6.[12] It goes without saying that the "probability" lag, of the first type, was avoided when taking this oscillogram by irradiating the gap with ultra-violet light. Data for high pressure arcs in the inert gases are not available.

High Pressure Arcs

The fifth and last conducting stage, the arc stage, is reached when the cathode becomes capable of abundant electron emission, either thermionic or field emission. This makes possible the essential manifestation of the arc condition which is a low voltage drop, decreasing or remaining essentially constant with increasing current.

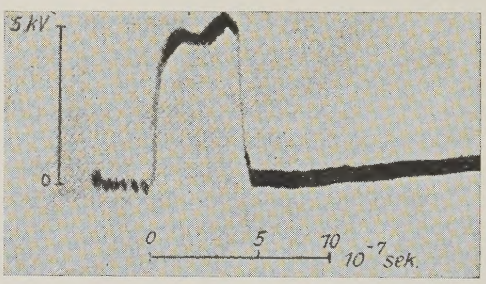

Fig. 6. Oscillogram of breakdown of sphere gap in air

The time lag is 1/10 μsec (Rogowski)

Arcs at atmospheric or higher pressure are distinguished from low pressure arcs by one important characteristic, namely, *the ionization in the arc path is maintained by the high temperature of the gas.* Several different methods of measurement agree in indicating that this temperature is about 5,000 deg K for arcs in air. Calculation, based upon the Saha equation for thermal ionization, shows that this temperature is sufficient to maintain the required degree of ionization. The calculated temperature for pure nitrogen is slightly higher, namely 5,400 deg, while the temperature for pure copper vapor at atmospheric pressure would be much lower, namely, 3,500 deg K. Approximately $^1/_2$ per cent of copper vapor mixed with the gas would account for all the

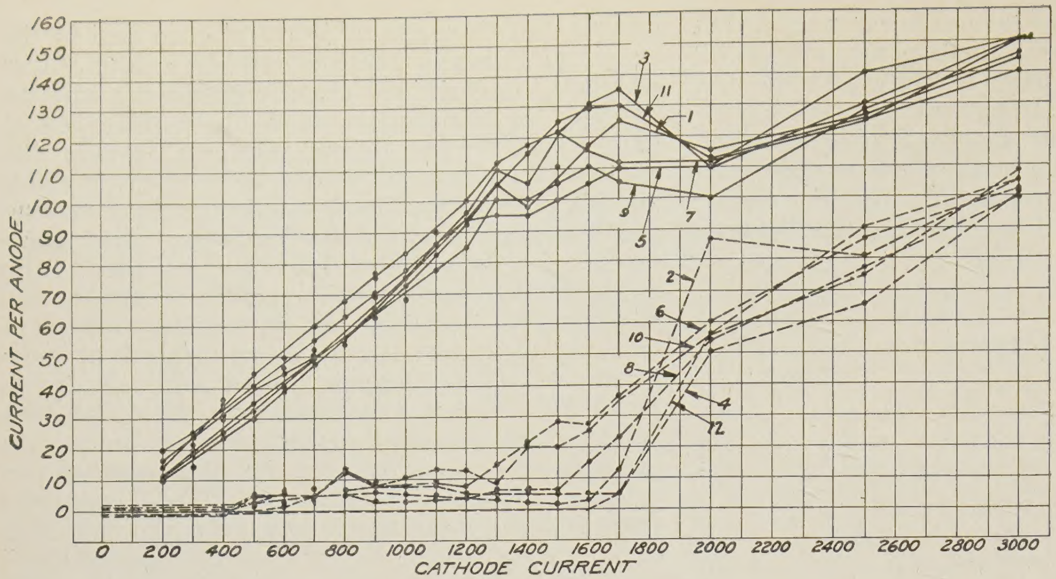

Fig. 7. Division of current between parallel connected anodes in a mercury arc rectifier, showing stability resulting from "positive resistance"

The rectifier was operated 6-phase, with one odd numbered anode and one even connected in parallel, forming 6 pairs

observed temperatures of arcs in air. It appears probable that a small amount of metal vapor always is present in the arc stream. Small variations in this amount would account for the variations in arc drop that have been observed.

Temperatures of arcs in monatomic gases have not been measured. Theoretical temperatures required to maintain thermal ionization of the arc stream are approximately 3,700, 5,500, 7,000, and 8,000 deg K, for mercury, argon, neon, and helium, respectively. A small amount of metal vapor, if present, would reduce the temperatures of neon and helium arcs to nearly the same values as those of argon and air.

Electron emission from the cathode in high pressure arcs is produced by 1 of 2 mechanisms: (1) It generally is agreed that the emission from tungsten and carbon electrodes is purely thermionic; (2) in the case of the other metals, emission appears to be "field emission," produced by the strong electric field of the positive ions close to the cathode, the same as in the mercury arc. (See discussion of mercury cathode under heading "Low Pressure Arcs.")

The negative resistance of high pressure arcs is accounted for at once by the fact that the ionization in the arc path is maintained by temperature, for this thermal ionization is an equilibrium condition, in which as many ions are formed per second as disappear by recombination, and no energy loss is involved in recombination. The only loss of energy therefore is the radiation and conduction of heat from the arc stream. This is proportional, per unit length, to the circumference of the arc stream, and hence increases as the first power of the diameter, whereas the conductivity increases as the cross section, that is, the square of the diameter.

Low Pressure Arcs

In discussing low pressure arcs, it will be convenient to discuss separately the phenomena at the cathode, in the arc stream, and at the anode.

The cathode of the mercury arc has been the subject of extensive investigations, the present status of which may be summarized as follows: The current density at the cathode is 4,000 amp per square centimeter of which at least 80 per cent, and probably 95 per cent, is carried by electrons. The remaining 5 to 20 per cent carried by positive ions forms a positive-ion space charge in front of the cathode, sufficient to give an electric field of approximately 500,000 volts per centimeter at the cathode. This is precisely the field strength required to produce a spark between clean cold electrodes of ordinary roughness in high vacuum. It is believed therefore that this field is responsible for extracting the electrons from the surface of the mercury. It is true that the quantum-mechanical theory requires voltage gradients of more than 20 times this value in order to produce field currents from smooth electrodes; but there is no reason for expecting the surface of the mercury to be smooth under these intense fields. The temperature at the cathode is

Table IV—Life Tests of Barium Coated Nickel Cathodes in Neon (From Measurements by Dr. L. R. Koller)

Neon Pressure, Mm	Hours Life at 1 amp	2 amp	3 amp	5 amp
0.100	$2\frac{3}{4}$		$1\frac{1}{4}$	
0.400	296	48	119	29
0.600	287	243	162	
1.500				1,069
2.000				1,626
3.500				2,370+

between 120 and 200 deg C—hence too low for any thermionic emission; and the impact of mercury ions of this velocity has been shown to produce no appreciable electron emission. However, the impact of the ions does produce rapid evaporation of mercury, blowing the ions away so that the "cathode spot" is compelled to move continuously and rapidly. Measurements on power rectifiers indicate that the

current is furnished by many small cathode spots, each contributing approximately 35 amp.

In thermionic cathodes, the most important phenomenon is positive ion bombardment of the cathode. This may produce 2 effects: disintegration and heat. If the ions strike the cathode with an energy of more than 25 volts, they disintegrate it, that is, knock off atoms of the cathode material; if their energy is less than about 25 volts, they have no effect other than to raise the temperature of the cathode. With ample thermionic electron emission and sufficient vapor pressure to furnish the needed ions (see subsequent discussion), the voltage drop adjusts itself automatically so that it is safely below the disintegration value. The heating effect is also negligible at low pressures, namely, between 1 and 100 microns. At higher pressures, from 1 mm to 5 cm (of mercury), concentration of the arc is sufficient so that its heating effect on the cathode must be allowed for.

The range of pressures from 1 mm to 5 cm exhibits another interesting characteristic, namely, an inhibition of evaporation of cathode material and of thermionic coating material, such as barium and thorium. A part of this inhibition is mechanical interference with evaporation by the atoms of the gas, the same mechanism that limits evaporation from filaments in gas filled lamps. It is believed, however, that the most important factor in the prevention of evaporation is ionization of the escaping atoms by contact with ions and excited

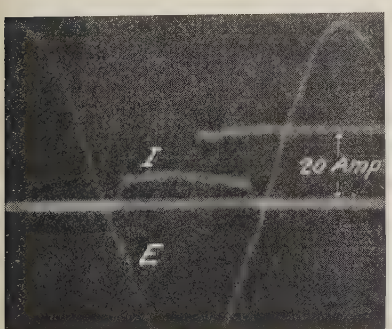

Fig. 8. Oscillogram showing current I and voltage E through a 1/4-in. hole in mercury vapor at 17 deg C

The current remains constant while the voltage increases from 20 volts to 160. The 20-amp trace is for calibration

atoms of the gas. The excited atoms are in general more numerous than the ions, so that when their energy is sufficient, namely, more than the ionizing potential of the escaping material, ionization by excited atoms is the more likely process. Thus barium atoms escaping from a barium coated nickel cathode have a high probability of being ionized and being driven back to the cathode before they can escape, while nickel atoms, the ionizing potential of which is higher than the energy (4.66 volts) of metastable mercury, will not be ionized and will escape. Hence a cathode that is operated at so high a temperature that its life in vacuum or in a gas at very low pressure would be only a few hours, may live many thousands of hours at pressures of from 1 to 50 mm. Table IV shows a few values of the life of barium coated cathodes operated at different vapor pressures in neon.

The arc stream of a low pressure arc differs from that of high pressure arcs in that the temperature of the atoms is low, so that ionization must be maintained by electron impacts. However, recombination of ions and electrons occurs so seldom at low pressures that its effect is negligible, and the principal loss of energy from the arc stream is diffusion of electrons and ions to the walls of the container. This diffusion, like that of heat, is proportional to the circumference. Hence the energy required to maintain the ionization, and therefore the voltage gradient along the discharge, is inversely proportional to the diameter of the tube.

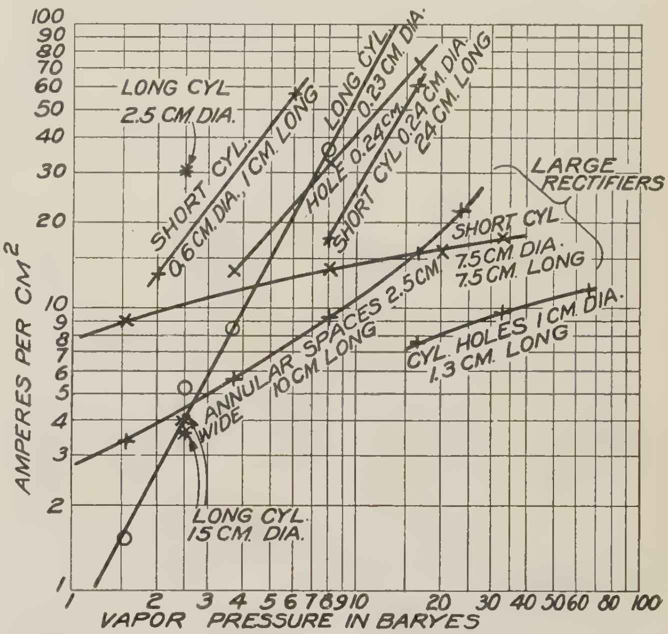

Fig. 9. Observed maximum current density in mercury vapor arcs as function of pressure

The limit is set by the approach to 100 per cent ionization of the vapor

Since low pressure arcs in general must be confined, they cannot expand with increase in current; hence the arc resistance is positive except for an initial stage. This initial stage represents the transition from single impact ionization to cumulative ionization, the latter process being the more efficient (hence the negative resistance) because it utilizes some of the energy of the excited atoms for ionization instead of allowing all of this energy to be radiated. It takes place in the range of current from 1/10 to 1 amp per square centimeter. At higher currents, the resistance is positive. Such arcs are therefore stable and may be operated in parallel. In Fig. 7 is shown the current in 6 pairs of anodes of a mercury arc rectifier, connected 2 by 2 in parallel. It may be noted that 1 anode of each pair carried all the current during the initial stage, until the negative resistance period was passed, but thereafter the 2 shared the current nearly equally.

A question of special interest is the maximum current carrying capacity of low voltage arcs. Theory indicates that when all the atoms in the arc stream are ionized no further increase in conductivity

can be obtained except by increasing the velocity of the electrons, that is, by raising the voltage. Experimentally it is found that when the ionization reaches approximately 50 per cent of the total number of atoms, the voltage rises almost abruptly. In Fig. 8 is shown an oscillogram of the current through a $^1/_4$-in. hole in a carbon disk in mercury vapor at a pressure of 1 micron. It may be noted that the voltage rises abruptly to the limit of the 60-cycle a-c wave (160 volts crest) after the current reaches 10 amp, and that the current increases only slightly with this increased voltage. Table V gives the maximum observed currents in this test at a series of different pressures. In Fig. 9 are shown the maximum current densities that have been observed in low pressure mercury arcs of all kinds for which data are available. It may be observed that these values agree well with the experimental ones given in Table V, with the exception of the large current mercury rectifiers; in these the high mercury vapor pressure and large cross section offer conditions favorable to high temperature of the arc stream with consequent low vapor density. A temperature of 2,000 deg K would account for the observed values.

Phenomena at the anode of a low pressure arc are very simple. An anode drop, which may be positive, zero, or negative, according as the anode area is smaller, equal to, or larger than the cross section of the arc, delivers heat to the anode but has no other effect. The heating is equal to the energy of the impinging electrons times the current, plus the heat of condensation of the electrons which is approximately 5 volts (work function of the anode material) per ampere. With unidirectional potential this is the only anode phenomenon.

Table V—Maximum Current Capacity of Mercury Vapor; Current Through Hole 0.6 Cm in Diameter and 1 Cm Long

Mercury Vapor Pressure, Mm	Max. Current Density, Amp per Sq Cm
0.0091	30
0.0065	93
0.013	138
0.021	181
0.026	200
0.048	475

With alternating potential, as in a rectifier, there is an additional phenomenon of great importance, namely, the bombardment of the anode, when negative, by positive ions. With multianode rectifiers these ions may be drawn from the arc stream. In single-anode tubes they are the left-over ions that remain in the space at the end of the conducting cycle and their effect is by no means negligible when the anode voltage reverses rapidly. For example, in a typical test with 2,000-cycle sine wave alternating potential and pure resistance load, the disintegrating effect of mercury ions destroyed 0.02 g of anode material per ampere per hour at 3,000 volts (rms), and was roughly proportional to voltage. At 60 cycles with ordinary reactive loads, the corresponding loss to be expected on the basis of these tests is roughly 0.0007 g per ampere per hour, while with 60 cycles and pure resistance load, is only 0.00004 g per ampere per hour at 3,000 volts. In this latter case most of the ions have disappeared before the anode voltage becomes high enough to produce serious disintegration.

The effect of positive ion bombardment of the anode on its ability to withstand reversed voltage, which is a figure of merit of a rectifier, is a subject that is receiving much attention at present. No clear picture of the mechanism of this effect is as yet available.

Most of the phenomena dealt with in this paper are discussed in greater detail in the following treatises:

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3. Electrical Discharges in Gases, K. T. Compton and I. Langmuir, pt 1, *Rev. of Modern Physics*, v. 2, 1930, No. 2, p. 123–242.

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Lightning Performance of 220-Kv Lines

Because of the scarcity of published records of lightning performance of 220-kv power transmission lines, the A.I.E.E. lightning and insulator subcommittee* has attempted to collect such data by means of a questionnaire sent to the various companies operating 220-kv lines in the United States and Canada. The data thus obtained is summarized in this paper.

LIGHTNING PERFORMANCE of transmission lines has been intensively studied, investigated by field research and operating records, and predicted by theory during the last decade. The results of much of this work have appeared in technical publications in the past; but in the 220-kv transmission field actual published operating records have been very few except for one system.[1]

In view of the large amount of organized lightning investigation and research work done and published on lines operating in the 132-kv range and below, it was felt that a more complete picture of 220-kv line operation under lightning conditions would be of interest and value at this time. This picture the present paper attempts to give, up to and including 1933, for the 220-kv lines in the United States.

Collection of Data and Lines Considered

The collection of data on which this paper is based was effected by a questionnaire sent to the several operating companies whose prompt response herewith is acknowledged. The questionnaire was framed to obtain information on many of the constructional and operational features of the lines that were considered as having any bearing on the lightning performance of the lines. Detailed characteristics of many of the lines, too voluminous to give here, have been reported before (see bibliography at end of paper). Analysis of the lightning data on these lines has been made in the light of existing and more recent theories of lightning performance of lines.

The 220-kv lines discussed here are situated in territory where the lightning conditions vary from light to severe. More than 60 per cent of the lines (right of way) is situated in California where isoceraunic data indicate 5 lightning storms per year; some 25 per cent is near the middle Atlantic coast, in New Jersey and Pennsylvania, where the storms average about 35 per year; 7 per cent is in New England where some 24 storms per year are recorded; and 7.5 per cent in Canada on a 187-kv line where lightning storms average some 15 per year. This 187-kv line in Canada has been included because it represents a line in the higher voltage class (above 132 kv); operating records for 6 years are available, and also the line embodies some of the extensively discussed features of lightning protection. The 287-kv Boulder Dam line has been included, although not yet in operation, because the general design of this line from the point of view of lightning disturbances is interesting.

The classification of all lines as regards the type of circuit is given in Table I. The types of towers employed on these lines are illustrated in Figs. 1 and 2. These types of towers are referred to the various lines in column 9 of Table II.

Tower Design

Tower design in recent years has been mostly of the type employing flat-top configuration with the 3 line conductors in a horizontal plane. The conductor spacing used with this type of tower varies from 20 ft in mild lightning districts to 28.5 ft in the more severe lightning territory.

For the flat-top single-circuit towers the conductor height at suspension towers ranges from 35 and 44 to 66.5 ft, although a height of 77 ft is used on the 287-kv lines; for the 2-circuit towers the corresponding height of conductor ranges from 85.5 to 112 ft.

Ground Wires

All lines except 3 are built with one or more ground wires. Two of the lines (Nos. 8 and 9 in Table II) which have no ground wire are in mild lightning territory, and the third line (No. 5), which when first built had no ground wire, has since had 2 ground wires added over about 35 per cent of the line. This line is in severe lightning country.

The more recently built lines, except in mild lightning terrain, have been built with 2 ground wires per tower line. On 5 of the lines where twin tower construction is used on the same right of way, 2 ground wires are used per tower, making a total of 4 for the 2 circuits.

Table I—Mileage of 220-Kv Line (Right of Way) in the United States

Type of Circuit	Miles
Single circuit, single right of way	566
Double circuit, single right of way	1,064
*Double circuit 187-kv, single right of way	136
Total single tower line	1,766
Twin tower line	770

*This line in Canada.

Full text of a paper prepared by the lightning and insulator subcommittee of the A.I.E.E. committee on power transmission and distribution, recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Sept. 14, 1934; released for publication Sept. 14, 1934. *Not published in pamphlet form.*

*Personnel of A.I.E.E. lightning and insulator subcommittee: Philip Sporn, *chairman;* I. W. Gross, *secretary;* C. L. Fortescue, K. A. Hawley, J. Allen Johnson, W. W. Lewis, J. T. Lusignan, and F. W. Packer.

1. For numbered references see bibliography at end of paper.

Table II—Design Features and Lightning Performance of 220-Kv Lines

1 Line No.	2 Name of Company	3 Line Designation	4 Date First in Service	5 Length of Line (Miles)	6 Avg Tower Span (Ft)	7 No. of Circuits	8 Circuits per Tower	9 Tower Design (Fig. No.)	10 Ground Wires per Tower	11 Height of Ground Wires Above Cond. at Tower (Ft)	12 Ground Wire Location (See Figs.) (Feet) A	 B	13 Cond. Height Above Ground at Tower (Ft)	14 Conductor Spacing (Ft)	15 Conductor Clearance at Tower In.	 At Deg Swing
1	New England Pwr. Assn.	Comerford-Tewksbury	10/ 1/30	126.4	590	2	1	1	2	15	11	...	44	23.5	86	45
2	Pa. Water & Pwr. Co.	Safe Harbor-Westport	12/ 7/31	92.0	1,020	1	1	1	2	24.5	7.1	...	60	28.2	61	51
3	Pub. Serv. Elec. & Gas Co.	Roseland-Bushkill	4/ 8/32	45.7	1,150	1	1	1	2	13.8	14.3	...	59	28.5	72	49
4	Pub. Serv. Elec. & Gas Co. and Philadelphia Elec. Co.	Roseland-Plymouth Mtg.	8/31/30	46.2 29.6	1,050	1 1	1 1	1 1	2 2	13.8 16.0	14.3 4.0	... ...	59 62	28.5 25.5	72 60	49 53
5	Pa. Pwr. & Lt. Co.	Wallenpaupack-Siegfried	4/11/26	65.0	1,110	1	1	1	0–2	10.5	11.3	...	66.5	22.6	54	45
6	Pa. Pwr. & Lt. Co. and Philadelphia Elec. Co.	Plymouth-Siegfried	2/18/28	48.7 9.9	1,270	1	1	1	2	13.3 16	13.1 12.7	... ...	66.3 63.8	26.3 25.5	73 60	45 53
7	Philadelphia Elec. Co.	Conowingo-Plymouth Mtg.	3/ 5/28	57.6	1,170	2	1	1	2	16	12.7	...	63.8	25.5	60	53
8	Pacific Gas & Elec. Co.	Pitt Lines Nos. 1 & 2	9/—/22	202	720	2	1–2	1–2	0	..	..	...	45 85.5	19 15	54	?
9	Pacific Gas & Elec. Co.	Tiger Creek Nos. 1 & 2	6/—/31	109	790	2	1–2	1–2	0	..	..	...	45 8.95	19 17	60	?
10	So. Calif. Edison Co.	Vincent (Big Creek-Magunden)	1/24/28	128	1,470	1	1	1	2	12.8	10.3	...	55	22.3	72	30
11	So. Calif. Edison Co.	Vincent (Magunden-Gould)	11/14/26	95	1,150	1	1	1	2	12.8	10.3	...	55	22.3	72	30
12	So. Calif. Edison Co.	Big Creek 2A-Big Creek 3	7/15/28	6	1,090	1	1	1	2	13.8	10.3	...	55	22.3	72	30
13	So. Calif. Edison Co.	[8]East Big Creek [8]West Big Creek	4/14/14 11/18/13	250 260	775 810	2	1	1	1	11	8.3	...	35.2	17.3	72	30
14	So. Calif. Edison Co.	East & West Lighthipe Laguna Bell	10/30/27	6.7	1,110	2	1	1	2	13.3	10.3	...	55	22.3	72	30
15	So. Calif. Edison Co.	East & West Gould Laguna Bell	8/ 1/23 11/ 3/23	22.9	1,230	2	1	1	1	12.5	10.3	...	55	22.3	72	30
16	So. Calif. Edison Co.	Lighthipe-La Presa	2/27/30	9.5	880	2	2	2	1	16.3	15.5	...	111	20	72	30
17	So. Calif. Edison Co.	Lighthipe-Long Beach Steam	6/16/28	9.4	900	2	2	2	1	16.3	16.5	...	111	20	72	30
18	City of Los Angeles, Calif., Dept. of Water & Pwr.	[1]Boulder Dam	Not in service	265.5	950	2	1–2	1 2	2 2	31.5 31.5	7.5 0.1	... ...	77 112	32.5 24.5	84	43
19	Shawinigan (Can.) Water and Pwr. Co.	[2]Nos. 25 & No. 26	8/—/27	136	910	2	2	2	2	10	..	5.0	74	12.0	41	45

1. Designed for 287.5 kv. 2. Designed and operated at 187 kv. 8. Operated at 150 kv before 1924; lightning performance given from 1929 on.

Since the location of the ground wires with respect to the line conductors has been given much theoretical attention, it is interesting to analyze the construction of 220-kv lines in this regard. The vertical height of the ground wires above the conductors, at the towers, varies from 10.5 to 24.5 ft, and reaches 31.5 ft for the 287-kv line; the average height is from 14 to 16 ft. As regards locating the ground wire in such a position above the line conductor as to provide a shield against the line conductor being struck, it is interesting to note that on every 220-kv line, and even on the 287-kv line, the ground wires on flat-configurated towers are set closer to the tower center line by some 4 to 15 ft than is the line conductor immediately below it. The notable exception to this practice of "insetting" the ground wire is on the one 187-kv line where the 2 ground wires "overhang" the line conductor by 5 ft.

Line Insulation and Tower Clearance

The impulse voltage insulation[2] at the tower is indicated for each line in columns 15 to 18, Table II; the values for suspension insulators alone (omitting the effect of arcing shields, if any) vary from 1,300 kv to more than 2,000 kv with a 1x5-μsec minimum positive impulse wave. The average value for lines in severe lightning areas is about 1,700 kv.

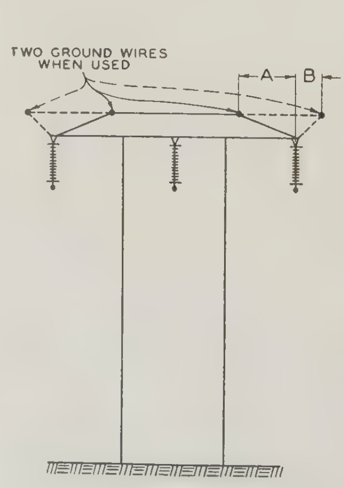

Fig. 1. Single-circuit tower

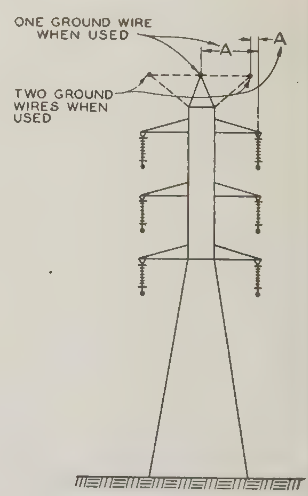

Fig. 2. Double-circuit tower

Table II Continued—Design Features and Lightning Performance of 220-Kv Lines

16	17		18	19	20	21		22	23	24	25	26	27	28	
Clearance Impulse (1x5-μsec pos.) Flashover at Tower, kv[7]	Suspension Insulators		Insulator Impulse (1x5-μsec pos.) Flashover, kv[7]	Type of Country	Nature of Soil	Tower Footing Resistance, Ohms		Additional Grounds at Tower	Lightning Severity	Avg Line Outages per 100 Miles of Line per Year	Grading Shields Used	Tower Flashovers per Year Avg[10]	Isoceraunic Factor	Outages per 100 Miles of Line per Year at Isoceraunic Factor of 50	Line No.
	No.	In. Spacing				Avg	Max.								
1,740	15	$5\frac{3}{4}$	1,670	Rolling, hilly, flat	Various	300	1500+	None	Severe	3.7	Ring & ring	1.0	24	7.7	1
1,250	20	5	1,930	Rolling	Clay, shale, sand (poor)	[3]25 70	[3]85 400	Counterpoises & rods—salted	Severe	0.55	None	0.5	36	0.76	2
1,460	16	$5\frac{3}{4}$	1,775	Hilly, flat	Rock, clay, marsh	26 [4]18	300+	Counterpoises (Some)	Severe	1.10	Ring & ring	0.5	35	1.6	3
1,460 1,230	16 16	6 $5\frac{3}{4}$	1,840 1,775	Hilly, flat rolling	Rock, clay sand	6.1 [6]3.4	105 [6]12.5	None	Severe Mild	3.5	Ring & ring Ring & ring	1.33	33	5.3	4
1,110	14 to 16	$5\frac{3}{4}$	1,565 1,775	Mountainous to rolling	Rock, sand, clay	40.2 [4]25.3	330	Counterpoise (Some)	Severe	[5]31.0	Ring & horn	51	35	44	5
1,480 1,230	16 14	$5\frac{3}{4}$ $5\frac{3}{4}$	1,775 1,565	Rolling, flat	Rock, clay	[12]16.1 [11]4.7	[12]61 [11]10.4	None	Mild Severe	1.7	Ring & ring None	1.5	35	2.4	6
1,230	16	$5\frac{3}{4}$	1,775	Hilly, rolling	Rock, clay	[6]10	[6]40	Counterpoise & ground rods	Mild	5.5	Ring & ring	2.0	35	7.8	7
1,110	13	5 $5\frac{1}{2}$	1,300 1,410	Mountain, hilly Flat	Rock, clay Sand	...	...	Ground plate at One tower leg	Mild to Light	1.0	Corona shield	2.0	5	10	8
1,230	13 to 20	$5\frac{3}{4}$	1,460 2,200	Mountain, hilly Flat	Rock, clay	...	...	Ground rod at One tower leg	Light	0.6	Corona shields	0.7	5	6	9
1,460	13	$6\frac{1}{4}$	1,590	Mountain, hilly	Rocky	...	...	None	Light	0.9	Ring & horn	1.2	5	9	10
1,460	13	$6\frac{1}{4}$	1,590	Mountainous to flat	Rock, sand clay	...	...	None	Light	2.75	Ring & horn	2.6	5	27.5	11
1,460	13	$6\frac{1}{4}$	1,590	Mountain	Rocky	...	...	None	Light	0	Rings	0	5	0	12
1,460	12	$5\frac{3}{4}$	1,355	Mountainous to flat	Rock, clay sand	...	...	None	Light	0.31	Rings	0.6	5	3.1	13
1,460	13	$6\frac{1}{4}$	1,590	Flat	Sandy	...	...	None	Light	0	Ring & horn	0	5	0	14
1,460	13	$5\frac{3}{4}$	1,460	Hilly, flat	Rock, sand	...	...	None	Light	1.7	Ring & horn	0.4	5	17	15
1,460	15	$6\frac{1}{2}$	1,860	Flat	Sandy	...	...	None	Light	2.6	Rings	0.2	5	26.3	16
1,460	15	$6\frac{1}{4}$	1,800	Flat	Sandy	...	...	None	Light	0	Rings	0	5	0	17
1,700	24	5	2,300	Mountainous to flat	Rock, sand gravel, clay	...	...	2 Counterpoises per tower line	Mild Light	..	Ring & ring	...	..	..	18
850	10	$4\frac{3}{4}$ 5	980 1,025	Hilly	Rock, sand Gravel	[9]200+	[9]300+	Counterpoise (being installed)	Mild	5.6	None	13.6	15	18.7	19

3. After installing auxiliary grounds. 4. After installing counterpoises. 5. Past 6 years only. 6. Measured with ground wires in place. 7. Based upon "Flashover Voltages of Insulators and Gaps," Elec. Engg., v. 53, June 1934, p. 882–6. 9. Measurements on representative towers. 10. Found by inspection. 11. On 9.9-mile section. 12. On 48.9-mile section.

Evaluation of the impulse strength of clearances between line wires and structure, at the tower, have been based upon gap breakdown characteristics[2] of the clearance distance with the conductor swing (angle of swing) for which the line was designed. This angle of swing has been reported as varying from 30 to 53 deg for the different lines. Corresponding impulse strengths for the clearances reported vary from 1,110 to 1,740 kv, that is, of the same order of magnitude as the insulator flashover voltages, although it may be expected that the extreme angle of swing will not occur coincident with severe lightning conditions.

Tower Footing Resistance and Counterpoises

Most of these lines extend through considerable hilly, rough country where ground conditions are poor (see Table II, columns 19, 20, and 21) and normal tower footing resistances are high. Average tower footing resistances in the order of 16 ohms or more are common, and one line reports an average of 300 ohms.

On 6 of the 19 lines counterpoises are used in varying extent to lower the normal resistance. That this means is effective in lowering the measured resistance is clearly indicated (column 21, Table II).

Since the counterpoise has come into recent and somewhat extensive use as a means of reducing tower footing resistance in order to secure the expected protection from lightning, a brief description of the counterpoises used at locations of high resistance on these lines may be of interest.

Line 2. From 4 to 8 wires per tower, each 50 ft long and terminating in 8-ft ground rods. Rods and wires salted. Also one continuous counterpoise $4\frac{1}{2}$ miles long of $\frac{3}{8}$-in. "copperweld" cable.

Line 5. Continuous buried 2/0 stranded copper cable, 2.8 miles long connecting 14 consecutive towers. Also "crowfoot" counterpoises for $19\frac{1}{2}$ miles of line (101 towers) each counterpoise consisting of 4 50-ft lengths of 2/0 stranded copper conductor buried 1 ft in the ground, extending 45 deg to the line and connected to the tower legs.

Line 7. Two 1,000-ft copper cables buried parallel to line and bonded to towers.

Line 18. Two $\frac{1}{4}$-in. black copper rods per tower line, buried 3 ft or less in ground. Wires run radially from the tower until 130-ft separation is reached, then parallel to line conductors.

Line 19. Single No. 6 B.W.G. galvanized iron wire now being installed, buried in the earth, over about 20 miles of right of way.

Mid-Span Lightning Strokes

In answer to the question "Have you any definite evidence of line or ground wires being hit by lightning (or evidence of arcing between conductors) in mid-span?" all companies reported "No" except 2. One of these 2 remarked: "Yes, 20 to 30 ft from the tower"; the other stated: "One instance of direct hit to conductors at mid-span (no tripout)." A third company reported "No," but believes from their records that the conductors frequently are struck.

Line Damage and Outages

Damage to insulators and conductors was indicated for all lines, as being of minor operating importance. The duration of line outages varied from 1 to 4½ min, except for the lines of one company which reported a duration from 10 to 20 min. This delay, however, appears to be attributable to operating practice rather than inability to put the line back in service.

For comparative purposes the line outages on each line have been converted to the number occurring per 100 miles of line (right of way) per year and, further, corrected by isoceraunic curves[3] to a yearly storm frequency of 50. Records of all lines, on the foregoing basis, are given in Table II, column 28, and a summary of average results in Table III.

Definite conclusions are rather difficult to draw from these records, although several features are outstanding when the outages are studied with line construction and lightning territory in mind. In severe lightning territory the line (No. 5) built and operated for some time without any ground wire, but now partially equipped with ground wire, has 10 times as many outages as other lines having ground wires and situated in similar territory. Although the larger number of outages may be attributed partly to the slightly lower insulation and clearances at the towers than used in more recently built lines, and the local lightning may be more severe, the greatest controlling factor is probably the absence of a ground wire.

Table III—Average Line Outages Caused by Lightning on 220-Kv Lines* in the United States

	Outages per 100 Miles of Line per Year	
	Actual	On Basis of 50 Storms per Year
Average all lines	3.3	9.8
All lines having ground wires (excluding No. 5)	1.6	7.0
Lines with ground wires in severe lightning territories	2.6	4.2
Lines with ground wires in light lightning territories	1.0	10.3
Lines without ground wires in light lightning territories	0.8	8.0
†187-kv line—2 ground wires, in mild lightning territory	5 6	18.7

*Excluding lines 18 and 19, Table II. †This line in Canada.

Lines in light lightning territory that have an outage record actually averaging in the order of 1 per 100 miles of line per year, give an indicated performance of 10 outages in an area experiencing 50 storms per year area against a corresponding outage record of 4.2 for lines specially constructed against lightning flashover. The special construction referred to comprises 2 ground wires placed high over the line to provide better shielding, higher line insulation, and, particularly, reduction in tower footing resistances.

The importance of low tower footing resistance is indicated in the outage records of lines Nos. 1 and 19. Line No. 1 is of twin tower construction, with 2 ground wires per tower line, but with tower footing resistances averaging 300 ohms. The outage record is correspondingly high, namely, 7.7 on the basis of 50 storms per year. Likewise line No. 19 (187 kv) with 2 ground wires placed well out over the line conductors to provide better shielding has an outage record of 18.7, and here again the average tower footing resistance indicated is more than 200 ohms.

The line (No. 2) having the best record has 2 ground wires placed well out over the line conductors and high (24.5 ft) above the conductors. This line has the highest insulation (insulators only) of any of the 220-kv lines although the conductor clearance (at 51-deg swing) is only nominal. One important thing to note about this line, however, is that normal tower footing resistances averaging about 70 ohms have been reduced by salted counterpoises and ground rods to about 25 ohms. This line has had an operating record over 2 years of 0.76 outages per 100 miles per year on a 50 isoceraunic basis, which is practically the same as the actual average performance record of all 220-kv lines in light lightning territory.

Summary and Conclusions

While, as before mentioned, the records of line performance are not sufficiently complete or clear cut to prove or disprove definitely the theories of lightning performance of high voltage lines that have been advanced during the past few years, it is believed the following conclusions applying to 220-kv lines may be drawn fairly from the records presented here:

1. The use of one or more ground wires on transmission lines results in a relatively large reduction in outages caused by lightning.

2. Low tower footing resistances, in addition to ground wires, further reduce line outages. From practical considerations, low footing resistances alone, without ground wires, are of little value in reducing outages.

3. The line, of appreciable length, having the best lightning performance record (line No. 2, Table II), actual as well as on a 50 isoceraunic basis, has high insulation, 2 ground wires high above the conductors and slightly "inset" from the vertical, and several towers equipped with counterpoise wires and ground rods both salted to bring the tower footing resistances down to about 25 ohms. Just how much each of these features contributes to the good performance of this line is not evident from the record.

4. Better shielding by locating ground wires almost directly over (or "overhanging") the line conductor does not materially improve the line performance, if tower footing resistances are high.

5. Lines built without special lightning protective features in light

lightning territory probably would be bad performers in severe lightning locations.

6. Damage to line and insulators initiated by lightning flashovers, is of negligible importance from a line service and maintenance point of view.

7. In the more severe lightning territory the use of counterpoise wires to reduce lightning troubles is being tried with considerable apparent success. More data, however, are required to prove the degree of benefits to be derived from the use of counterpoises.

8. Although lines in very light lightning territory sometimes indicate a relatively large number of outages due to lightning when referred to an isoceraunic factor of 50 (column 28, Table II), it must be remembered that these lines actually operate with a lightning outage record of the same order or better than lines in lightning infested country where special protective methods have been employed to reduce lightning troubles. In short, remedial measures are required in design of lines in proportion to the severity of the lightning territory traversed by the lines, if uniformly good performance is to be obtained.

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Vapor Conducting Light Sources

Developments in vapor conducting light sources made both in European and American practice are outlined in this paper. The various types of sodium and other vapor arc lamps are considered, together with the principal factors affecting their operation.

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RECENT development work on vapor conduction lamps has been devoted to 2 principal types of work. One of these is the perfection of the so-called "hot cathode," of various vapor resistant glasses, and of a-c operating circuits. The other type of work to which development has been devoted is a study of tubular versus bulbular lamp forms, of the factors affecting depreciation, and of an economic rating, i. e., the relative importance of life and efficiency.

While similarity of work and thought in the lamp development laboratories in the United States and abroad does at present result from the continuous and reciprocal interchange of information, a difference in product results from individual interests and emphasis.

Various Types of Hot Cathodes

Of the many forms of hot cathodes, a simple one consists of a few inches of 20-mil tungsten wire wrapped closely with 5-mil nickel wire, and coiled into a helix about 0.2 in. in diameter. This concentrated nickel-covered tungsten filament with a fused-on and activated coating of alkali-earth oxide is heated by a 10-amp 2.5-volt current to such a temperature that it will emit a 6 to 7 amp current for over 1,000 hr. Two such cathode electrodes assembled in a bulb of such dimensions as to give a sodium arc drop of 30 volts constituted the 10,000-lumen sodium lamp exhibited at the New York meeting of the A.I.E.E. on November 21, 1933. This was but a typical design and by changing the dimensions of the cathode and of the enclosing bulb, larger as well as smaller units have been made.

A similar arc rated at 60 watts has been marketed as the essential part of a small unit designed primarily for use in the physical and chemistry laboratory.

A similar cathode for 2-volt a-c operation in the center of an elongated bulb with cylindrical anodes at the ends of the bulb but connected in multiple, forms the a-c cathode, d-c arc sodium lamp developed by Philips in Holland and made by the General Electric Vapor Lamp Company in the United States. This was the sodium lamp used in the Balltown Road demonstration at Schenectady, N. Y., during 1933.

In contrast with the above type of electrode with a voltage gradient on the activated surface of the

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cathode, there is the uni-potential cathode of the type already used for several years in hot cathode neon and mercury arcs. This cathode is a cylinder of nickel coated with a fused-on and activated layer of alkali-metal oxide heated by an axially placed filament of tungsten. Such cathodes have been used in a sodium arc rated at 200 watts and intended for general use. Mercury lamps using practically this same cathode have been on the market for several years for use as low intensity sources of ultraviolet radiation for hygienic use in the home.

Hot cathodes of the type just described are heated independently of the arc, much as are a-c radio tube cathodes, and like the larger radio cathodes, require in some cases, a period of preliminary heating before high voltage or high current operation. An alternative type of cathode is one of such small heat capacity that a short initial period of glow discharge operation provides an adequate temperature for normal operation. Such a cathode has recently been used in a tubular type sodium arc made in Holland and referred to later. This type of cathode had previously been used in neon and mercury arcs of both foreign and domestic design.

Mention should also be made of circuit arrangements by which the heating current is automatically reduced or shut off in the former type of cathode so designed that the normal arc heating will maintain it at the proper emitting temperature. Thus the high current capacity and long life of the independently heated cathode is combined with the efficiency of the arc heated cathode by a slight complication of the operating circuit.

Vapor Resistant Glasses

The relation between the glass composition and the depreciation of vapor conduction lamps has always been known to be very important; this relationship became critical in the case of the sodium arc, for which it has been necessary in the last 2 years to develop a new type of glass specifically for its resistance to hot sodium vapor. While tubes and bulbs have been made of such a glass, the associated glass working difficulties have been such as to result in the use, especially in domestic sodium lamps, of a sodium resistant glaze applied to the inner surface of tubes and bulbs of ordinary glasses. Considerable experimental work is now being done on both glass and glaze compositions and will doubtless result in an improvement of the already fairly satisfactory materials.

The depreciation of sodium arcs can be almost entirely attributed to the cathode and to the glass bulb or tube. For efficiency, both must operate at a temperature which jeopardizes their effectiveness and so depreciation becomes a phase of a very complicated problem of lamp design and rating.

Tubular Versus Bulbular Lamp Forms

In addition to the obvious complexities of cathode design which had, however, already been extensively investigated for use in neon lamps, sodium arcs are being made in both bulbular and tubular forms with the greater emphasis on the latter abroad. For example, the Antwerp Tunnel and approaches are illuminated by a 100-watt unit in which a tube about 0.75 in. in diameter and 16 in. long is folded up in such a manner as to permit enclosure in a cylindrical vacuum jacket of 2.5 in. by 5 in. internal dimensions. A similar U-shaped unit 0.5 in. in diameter and 18 in. long, is enclosed in a jacket of 1.5 in. by 9 in. internal dimensions.

The serious limitation to a development of the tubular lamp is the necessity of inclosure in a vacuum jacket in order to insure that a satisfactory arc temperature is maintained by the arc energy and without any accessory heating.

Operating Circuits

The method of operation and type of circuit to be used with the sodium arc is still a matter of very divergent practice. The foreign tubular lamps have generally been for 220-volt a-c operation while one of the best known of the bulbular lamps has an a-c cathode but requires about 15 volts direct current for the arc. A physically very similar domestic bulbular lamp is, however, operated on the full wave rectifier principle thus securing the unflickering light of d-c operation and the circuit advantages of an a-c supply.

The 200-watt unit first described represents the domestic interest in a full a-c sodium arc. While the flicker of the light results in stroboscopic effects under certain conditions, this is thought to be of no importance in the applications now in mind.

Other Types of Arc Lamps

Closely parallel to this development of sodium arcs is that of an a-c mercury arc using arc-heated oxide-coated cathodes, a limited quantity of mercury, and a design of lamp tube such as to insure a normal mercury vapor pressure of about one atmosphere. On 220-volts alternating current, automatic starting, when cold, is secured and an efficiency of about 35 lumens per watt is obtained with inductive ballasting. In England, a street lighting demonstration is being made with 420-watt units of this type.

There are yearly reports of vapor and gaseous conduction lamps giving light of daylight quality. These are generally nitrogen or carbon dioxide Geissler tubes or mercury-amalgam lamps. The latter have long been a promising subject for investigation and still are laboratory curiosities. They require a temperature control for their satisfactory operation much more difficult to obtain than that needed for a sodium or an ordinary mercury arc.

Arc Efficiency Ratings

The possibility of operating sodium arcs on direct current and on alternating current with either resistive or reactive ballasting, has raised an old confusion as to the efficiency rating of arc lamps. Series a-c operation with inductive ballast reduces the energy loss per unit external to the arc proper to so

low a value that there is a temptation to use only the arc watts in calculating the lumens per watt. This method of rating is obviously the most nearly an absolute rating for laboratory purposes. Most of the published sodium arc efficiency ratings have been based upon constant current or upon inductive ballasted series operation, and 50 lumens per watt seems to be an average practical initial rating, consistent with a life of 1,000 hr or more and a depreciation about such as is characteristic of high efficiency incandescent lamps. Laboratory ratings very much higher than this have been obtained but only further experience will indicate their practicality.

Limits to Amplification

The amplification obtainable in a vacuum tube amplifier is limited by the noise in the circuit. Of the various sources of noise the most fundamental and inevitable is thermal agitation of electricity. Other sources are the influence of ions and of shot effect and flicker effect on the current in vacuum tubes, poor contacts, mechanical vibration, and hum from a-c cathode heating. These noises and their effects in limiting amplification are discussed in this paper. Although the natural noise level of an amplifier is exceedingly low, modern amplifiers have reached such a stage of perfection that their noise levels often are practically at the natural limit.

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NOISE in amplifiers is now a familiar term. Any one who has had his favorite radio hour ruined by static knows the effect of an incoherent background of noise. Although static was one of the first noises observed in radio amplifiers, its origin is really outside the circuits. At one time it seemed that other sources of noise of purely local origin, such as poor batteries, loose contacts, gassy tubes and induction from power lines, might be eliminated entirely so that the circuits would be capable of amplifying any signal, no matter how small. It was found, however, that the noise level cannot be lowered indefinitely; that there are limits below which, in the nature of things, noise cannot be reduced.

Of the sources of noise, the most fundamental and inevitable is thermal agitation of electricity. In a perfect amplifier all other noises would be reduced to a level below that of thermal agitation. Next in order comes the influence of ions and of shot effect and flicker effect on the current in the vacuum tubes. Under control to a greater extent, but nevertheless of a malignant nature, are the effects of poor contacts, mechanical vibration, and hum from a-c cathode heating. In dealing with these disturbances, the circuit and vacuum tube of the first stage of the amplifier are the most important, for here the signal being amplified is at its lowest level. When the signal is so faint that it is masked by the noise remaining as the natural limit of the circuit, then the only possible remedy is to raise the signal level.

The natural noise level is exceedingly low, yet modern amplifiers have reached such a stage of perfection that their noise levels often are practically at the natural limit. This is true not only of special amplifiers built for experimental purposes, but of many amplifiers used in commercial circuits. The natural limits to amplification which will be discussed in this review are therefore of very practical interest.

Thermal Agitation[1,2,3,4,5,6]

The free charge of any conductor is in random motion in equilibrium with the thermal motion of the molecules of the conductor and this flow of charge creates a random voltage across the terminals of the conductor. This voltage usually is observed in a system composed of an amplifier with an input circuit and an output device. Its mean-square value across the output device is given by the expression

$$V_{t_o}^2 = 4kT \int_0^\infty RG^2 df \tag{1}$$

where the symbols have the following meanings:

k is the Boltzmann gas constant and is equal to 1.37×10^{-23} watt-second per degree

T represents absolute temperature, degrees Kelvin

R represents the resistive component in ohms of the input impedance as measured across the input terminals of the amplifier

G represents the voltage gain of the amplifier, and is equal to the ratio of voltage across the output device to voltage across the input terminals of the amplifier

f represents frequency in cycles per second

R and G are in general functions of frequency

In the simple case where the amplifier has a constant gain over a frequency range F and no gain out-

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1. For all numbered references see bibliography at end of paper.

side of this range, and where R is also constant over the same frequency range and is at the normal temperature of 300 deg, the mean-square noise voltage across the input terminals of the amplifier is

$$V_t^2 = 1.64 \times 10^{-20} RF \tag{2}$$

This is the voltage that would be produced by a generator supplying to the resistance R the power

$$W = \frac{V_t^2}{R} = 1.64 \times 10^{-20} F \tag{3}$$

The power W, sometimes expressed as 1.64×10^{-20} watts per cycle, is independent of R and may be regarded as the apparent input power of the thermal agitation. It depends only on the frequency range of the amplifier, since the temperature cannot be varied conveniently or very effectively and it sets a lower limit to the possibility of amplifying electrical impulses of any kind. Any signal much smaller than the thermal noise would be masked hopelessly. The only factor under control in the noise equation is the frequency range F, which should be no greater than is needed for the transmission of the signal.

An example will illustrate the magnitude involved in this limit to amplification. When the signal is speech requiring a frequency band of 6,000 cycles, then the apparent power generated at the input of the amplifier by thermal agitation is 0.985×10^{-16} watts, which is about 138 db below the common reference level of 0.006 watts. (The level of 10^{-16} instead of 0.006 watts is being considered as a reference point for the decibel scale in communication circuits. This is approximately the level of thermal noise in a 6,000-cycle channel.) If the input resistance were one megohm the corresponding rms noise voltage would be 9.94 μv.

A signal represents a certain amount of available power, and when this is so small that it is near the thermal noise level it must be used efficiently to produce voltage at the grid of the amplifier tube.[7,8] Let the signal be supplied by a generator of voltage E and internal resistance R_1 which delivers power to a load resistance R_2, the combination forming the input circuit of the amplifier as shown in Fig. 1. The mean-square signal voltage on the grid of the amplifier tube is

$$V_{s0}^2 = \frac{E^2}{R_1^2}\left(\frac{R_1R_2}{R_1 + R_2}\right)^2 \tag{4}$$

However, the resistance required by eq 2 for the noise is the combination of R_1 and R_2 in parallel, so that the mean-square noise voltage on the grid of the amplifier tube is, from eqs 2 and 3

$$V_n^2 = WR = W\left(\frac{R_1R_2}{R_1 + R_2}\right) \tag{5}$$

Hence the signal-to-noise ratio is

$$\frac{V_{s0}^2}{V_n^2} = \frac{E^2}{WR_1}\left(\frac{R_2}{R_1 + R_2}\right) \tag{6}$$

In general, the internal resistance R_1 of the signal generator is fixed, so that R_2 is the only available variable. In the usual case of matched impedances where R_1 and R_2 are equal, the signal-to-noise ratio is 3 db poorer than in the ideal case where R_2 is made very large compared with R_1. This is one of the few examples where a mismatch of impedances is advantageous. The use of an ideal step-up transformer between R_1 and R_2 in Fig. 1 will be of no avail, so far as the thermal noise is concerned, because its effect in eq 6 will be only to replace R_2 by R_2/N^2 where N is the turns ratio of the transformer.

In some systems the impedance at the input of the amplifier is unavoidably small. It may be so small that the voltage of the thermal agitation of

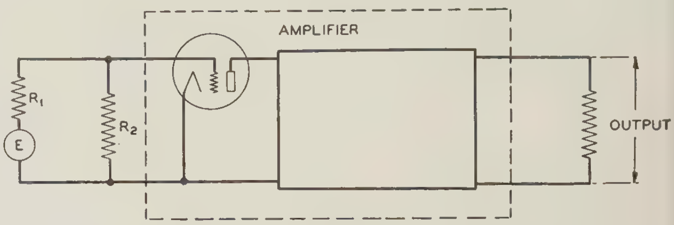

Fig. 1. Schematic diagram of a vacuum tube amplifier showing equivalent input circuit

the input circuit, even when amplified by the first tube, is lower than the noise voltage originating in the output circuit of that tube. Ideally, the noise in the plate circuit also should be caused by thermal agitation only, and the equations for it have been derived.[9,10] In practice, however, the noise in the plate circuit is found to be considerably greater, for reasons that will be discussed presently.

Shot Effect and Flicker Effect Without Space Charge

Early in the study of noise arising in vacuum tubes it was shown[1,11] that under certain conditions a noise is produced that depends on the fact that the electric current is a flow of discrete particles, the electrons, which are emitted from the cathode in a random manner. The random electron emission produces a statistical fluctuation in the current that flows through the tube and coupling impedance. This fluctuation, called the shot effect (German Schroteffekt, in analogy with the random scattering of shot from a shot gun), appears as noise in the output of the amplifier. When the current in the tube is limited by the rate of emission of electrons rather than by the space charge, so that the resistance of the tube is nearly infinite, then the shot effect produces a mean-square voltage across the output impedance of the amplifier given by [12,9]

$$V_{s0}^2 = 2\epsilon i \int_0^\infty Z^2G^2 df \tag{7}$$

in which

ϵ represents the charge on the electron and is equal to 1.59×10^{-19} coulomb

i represents space current in amperes

Z represents the magnitude in ohms of the coupling impedance

G represents the voltage gain of the amplifier from Z to the output

f represents frequency in cycles per second

For an amplifier having a flat frequency response curve over frequency range F the expression be-

comes, for the effective shot noise across the impedance Z

$$V_s^2 = 31.8 \times 10^{-20}\, iZ^2F \tag{8}$$

The expression holds quite accurately for tubes in which the cathode is made of either clean or thoriated tungsten and for high-vacuum photo-electric tubes, and it has been used in determining the charge on the electron.[13]

When an oxide coated cathode is used, fluctuations of a larger magnitude[14] are superimposed on the true shot effect. These fluctuations are inappreciable above about 10 kc, but increase rapidly in magnitude toward the lower frequencies. They also increase with the current at a faster rate than the shot effect fluctuations. This disturbance has been ascribed to a state of flux and change in the activating material on the surface of the cathode,[14,15] and the phenomenon has been called the "flicker effect" (from the analogy of a flickering candle).

There are 2 practical circuits in which the pure shot effect may set the ultimate noise level. One of these is the circuit in which the grid of an amplifying tube is left "floating" at its equilibrium potential as usually is done in the first stage of amplifiers used for ion counters and other instruments for measuring very small charges.[18,10] The grid then emits a few electrons and receives positive ions and electrons from the surrounding space. These currents are very small, but are not subject to space charge limitation so far as the grid is concerned. Because the grid impedance is very high, the shot voltage developed by the small grid current may exceed the thermal voltage of the grid impedance. The second circuit is that in which a photo-electric cell works into the amplifier.[19,20,21] Vacuum cells generate shot noise of very nearly the theoretical value given by eq 7, while gas filled cells give even greater noise.

The total noise generated in the output of the vacuum photo-electric cell is the sum of the shot noise and thermal noise across the coupling resistance R, as given by eqs 8 and 2. The mean square of the signal voltage, however, is $(\Delta iR)^2/2$ where Δi is the amplitude of the current variation. The ratio of signal to noise is then

$$V_{sg}^2/(V_t^2 + V_s^2) = 1.59 \times 10^{18} \frac{(\Delta i)^2}{F} \frac{R}{iR + 0.0516} \tag{9}$$

This equation shows the expected fact that for a given value of Δi it is better to keep the direct photo-electric current small (high modulation). It also brings out the curious result that when the direct voltage drop in the coupling resistance is much more than $^1/_{20}$ volt the noise is largely shot noise and the signal-to-noise ratio is independent of the coupling resistance, while if this voltage is much less than $^1/_{20}$ volt the thermal noise predominates and the signal-to-noise ratio is proportional to the coupling resistance.

Shot Effect and Flicker Effect With Space Charge

When, as in an amplifier tube, the current in the tube is limited partly or wholly by space charge rather than by the cathode temperature, then the conditions are changed[13,14,16] in 2 respects. First, while the electrons still are emitted from the cathode at random times, they must arrive at the plate in a more orderly manner. Simple statistical laws no longer apply, the flow of current is smoother and the fluctuations are greatly reduced. Second, the impedance of the tube is no longer infinite, but has a finite value. The equation for the shot effect (eq 7) now must be modified,[9,16,17] by substituting for the current i the quantity $j(\partial i/\partial j)^2$, where j is the total current emitted by the filament and $\partial i/\partial j$ is the rate of change of space current with emission current for the particular conditions used in the observation of the fluctuating voltage. Furthermore, in place of the coupling impedance Z the effective impedance Z_e of this in parallel with the tube resistance r_p must be used. The equation now reads

$$V^2 = 2\epsilon j \left(\frac{\partial i}{\partial j}\right)^2 \int_0^\infty Z_e^2 G^2 df \tag{10}$$

In the absence of space charge j and i are identical, $\partial i/\partial j$ is unity, and Z_e becomes Z, so that the equation then represents the pure shot effect. With increasing space charge the value of $\partial i/\partial j$ approaches zero and Z_e becomes smaller so that the shot effect becomes very small. Similarly the flicker effect, being connected with the process of emission and not with the subsequent history of the electrons, also is made ineffective by the space charge. In fact, in well designed tubes the fluctuation noise of both shot effect and flicker effect in the space current appear to be reduced to such an extent as to be negligible.

Ions in the Space Charge

The effect of ions in the grid current already has been discussed. Ions also may cause fluctuations in the plate current of the tube. The space charge which limits the current between cathode and anode consists of electrons in rapid progress toward the anode. A massive ion placed in this region travels much more slowly and contributes to the space charge for a much longer time than does an electron. While its own charge contributes little to the current, one ion may cause the current to change by the amount of hundreds of electrons during its flight through the space charge region, and the action of many ions would be additive.

Probably most of the ions existing in a tube are positive. Some of them are molecules of residual gas that have lost an electron by collision with an electron of the space current. Residual gas has been found to increase the noise of tubes, especially at the higher pressures. Observations at very low pressures are not conclusive, and it is not certain whether in any modern tubes the noise level is determined by the presence of residual gas.[9,14,19,20,21,22,23,24]

Positive ions may be emitted also by the cathode. These never can attain a high velocity because they remain in a region of low field intensity. They may be trapped for a time in the region of the potential minimum near the cathode before they finally pass to the grid or possibly become neutralized by an electron. In modern tubes with low temperature

filaments the effect of these ions is reduced greatly, yet still may account for a large part of the difference between the observed tube noise and the theoretical thermal noise of tubes.[14,25,26,27,28]

Noise in Commercial Tubes

Noise generated in an amplifier should consist largely of the thermal noise of the input circuit, to which is added the noise produced in the plate circuit of the first tube. It is convenient to consider that the tube noise comes, not from the plate circuit of the tube, but from a fictitious resistance R_G in series with the resistance R_c of the input circuit.[2] The effective thermal noise of the input circuit then is given by the expression

$$V^2 = 4kTF(R_c + R_G) = 1.64 \times 10^{-20}F(R_c + R_G) \qquad (11)$$

The tubes therefore may be rated conveniently in terms of R_G. The transformation to volts or to watts can be accomplished readily by eq 2 or 3. If, with a given tube and circuit, R_G approaches or exceeds R_c in value, the tube is responsible for an appreciable part of the total noise. The choice of another tube in which the ratio of R_c to R_G is more favorable then may be considered.

For the calculation of tube noise several formulas have been proposed, either entirely empirical[2] or with some basis on theory.[9,24,29] These formulas generally fail in the prediction of noise in tubes for the reason that the greater part of the noise in practical tubes is caused by things that have not been included in theory and that are still in a state of flux so far as manufacturing is concerned. It is best therefore to rely only on actual measurements of the noise in specific types of tubes. With modern tubes, the noise level of a given type of tube can be represented reasonably well by measurements made on a small number of samples.

Published data on noise of tubes are rather meager. The best series of measurements is that of Pearson,[10] which covers 4 Western Electric tubes at different frequency bands. These tubes are known commercially as types 102*G*, 262*A*, 264*B*, and 259*B*. The General Electric tube type *PJ*-11, designed specially for work at low frequencies, was studied by Metcalf and Dickinson.[24] They also give data, for the low frequency region, on the tubes known commercially as types 222, 240, 201, and 112. Johnson and Neitzert[30] have given data for the *PJ*-11 and the type '38 tube. Certain British tubes were studied by Moullin and Ellis,[29] and of these the type *AC*/2*HL* tube was found to have the lowest noise level. Brintzinger and Viehmann[31] studied a few German tubes. Of these the type *RE*-084 appears to have the lowest noise rating, but the data cannot be reduced to absolute measure.

In many of these studies the tubes were operated at voltages different from those usually employed. For these, the original papers should be consulted. In general for the best triodes R_G has a value of a few thousand ohms, while for screen tubes it has a value of a few tens of thousands. At the lowest voice frequencies the values may be somewhat greater.

Other Sources of Noise

While the more fundamental sources of noise have been discussed, it may be well to add some remarks on a few types of disturbance that often can be eliminated.

Noise From A-C Cathode Heating.[32–39] The indirectly heated cathode may be operated on alternating current when the tube is employed in radio frequency circuits. In audio amplifiers with gains in excess of 50 db, additional precautions must be taken to reduce the effects of the electric and magnetic fields of the heater and of coupling impedance between the heater and the other electrodes. Even under the best conditions, however, the hum level is of the order of 20 db above the tube noise measured with d-c heating.

Noise From Vibration.[32,33,39,40] Mechanical vibration changes the relative positions of the tube elements and hence causes disturbing noise. This is especially objectionable at audio frequency, although a radio frequency carrier may become modulated sufficiently to produce noise.

The remedy, used in the so-called "low microphonic" tube designs, is to stiffen the construction of the tube elements and to apply damping to their vibration, as well as to cushion the tube by a suitable mounting and to shield it from sound waves. The indirectly heated cathode is superior to the filamentary cathode in regard to noise from vibration.

Noise From Poor Insulation.[32,33,39] Noise arises from resistance changes at contacts and across thin films of conducting material deposited on insulating supports in the vacuum tube. Leaky capacitors may produce a similar noise.

Noise From Faulty Resistances. Many resistors in which the resistance element is a thin film are sources of noise. If no current flows in them only thermal noise is generated, but when direct current passes through them more noise is produced. The noise voltage is roughly proportional to the direct current. These resistors must be chosen carefully for circuit branches where current flows.

Signal-to-Noise Ratio[7,29,41,42]

In so far as noise is concerned, the merit of a transmission system is dependent not only on the amount of noise present, but also on the strength of the signal, so that a determination of the ratio of the signal level to the noise level is necessary. Fortunately, this ratio has a reference value for any given transmission system determined uniquely by the ratio of the signal to thermal noise in the input circuit. The ratio of the signal level to noise level is here the greatest the ratio ever can attain, because noise that originates at subsequent points in the amplifier contributes to the noise level without increasing the signal.

This fact provides a basis for the rating of amplifiers, the thermal noise of the input circuit being used as a comparison signal. For example, the noise output of an amplifying system may be 0.3 mw which falls to 0.2 mw when the input circuit is short-circuited. The thermal noise from the input cir-

cuit is then the difference between these 2 readings, namely, 0.1 mw, and the signal-to-noise ratio of the actual system is 3 times, or 4.8 db worse than its best possible value with a given signal. These data may be expressed in terms of an equivalent input resistance which has the advantage that the amplifying properties of the tube have been taken into account. This leaves for the engineer only the problem of selecting a tube having an input capacity of such a value that the construction of a relatively high impedance input circuit is possible.

So far, the discussion has been based upon the properties of amplifiers only, no mention being made of the effects of modulators, detectors, frequency converters, and other nonlinear devices on the signal-to-noise ratio. A detailed discussion of the noise in such devices is beyond the scope of this paper, but the relations in the most commonly used ones may be indicated and their general properties outlined.

First, consider a system composed of a radio frequency amplifier followed by a detector and a pair of headphones. A certain amount of noise will be heard in the phones if the gain of the amplifier is great enough. This noise is caused by the various components of the radio frequency noise beating together in the detector to form audio frequency components. Next, suppose that an unmodulated carrier is introduced into the amplifier. It will be observed that the audio noise in the phones increases. The increase in audio noise is produced by the radio frequency carrier beating with the radio frequency noise components and this increase is proportional to the strength of the carrier.

If a small percentage of modulation is added to the carrier, the audio signal-to-noise ratio in the phones will be determined by the properties of the amplifier in the same way as though the system were a straight amplifier without any detector. Comparison of the actual system with the ideal may be made by introducing the carrier into one of the amplifier stages subsequent to the input, and then measuring the audio noise with the input circuit in its normal condition and again with the input circuit short-circuited. The ratio of these 2 energy values gives the ratio of the equivalent input resistance of the actual system to the equivalent input resistance of the noisy amplifier alone. The ratio of the ideal signal-to-noise ratio to the actual one may be found by dividing the difference between the 2 audio energy readings by the reading taken with the input circuit in its normal condition.

If the percentage of modulation of the carrier is large, the system will be noisier because there will be appreciable audio noise components caused by beats between the side bands and the radio frequency noise components. Again, if the carrier level is not large compared with the noise level in the amplifier, the system will be noisier because the beats between the noise components are appreciable compared with the beats between carrier and the noise.

The same considerations apply to the first detector in a double-detection receiving system. If, as is usual, the beating oscillator voltage is large compared with the noise components, then the frequency band of the noise will be shifted in position in the same manner as the signal, and the signal-to-noise ratio of the system will be unchanged by the frequency conversion.

The signal-to-noise properties of any system are considered satisfactory when the total output noise differs only slightly from that produced by thermal agitation in the input circuit alone, and this difference may be measured by eliminating the input thermal noise (as by the short-circuit method) and noting the change produced in the output noise.

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High Velocity Streams in the Vacuum Arc

The high velocity streams of particles in the vacuum arc have been subjected to a detailed study, and the results are presented in this paper, together with a discussion of many of the phenomena involved. Experimental determinations of the relations between arc current, mass of condensed metal, pressure in the arc tank, force between electrodes, and velocity of the vapor stream are included. Results with several different electrode materials are presented.

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THE PRESENT paper is in part a continuation of work recorded in a former paper entitled "Forces of Electric Origin in the Iron Arc" (A.I.E.E. Trans., v. 51, 1932, p. 556–63), and in part suggested by the work of R. Tanberg reported in a paper "On the Cathode of an Arc Drawn in Vacuum" (*Phys. Rev.*, v. 35, 1930, p. 1080–9). The former paper contains curves of arc current against force between electrodes for an iron arc in air at atmospheric pressure. Under the caption "Tests on the Iron Arc Between Fixed and Moving Electrodes" the present paper discusses this relation for the iron arc in a vacuum. The remainder of the paper is devoted to a check on Tanberg's measurement of the velocity of the vapor stream emitted from a copper cathode, and to an extension of this work to vapor streams from both anode and cathode of 11 different materials.

Full text of a paper recommended for publication by the A.I.E.E. committee on electric welding, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Oct. 16, 1933; released for publication July 12, 1934. *Not published in pamphlet form.*

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Instrument for Measurement of Impulses

To permit the study of high current arcs, the impulse caused by the application of current for a short known period is measured. Because of the destructive action of a heavy current arc it is impracticable to measure a steady continuous force. The instru-

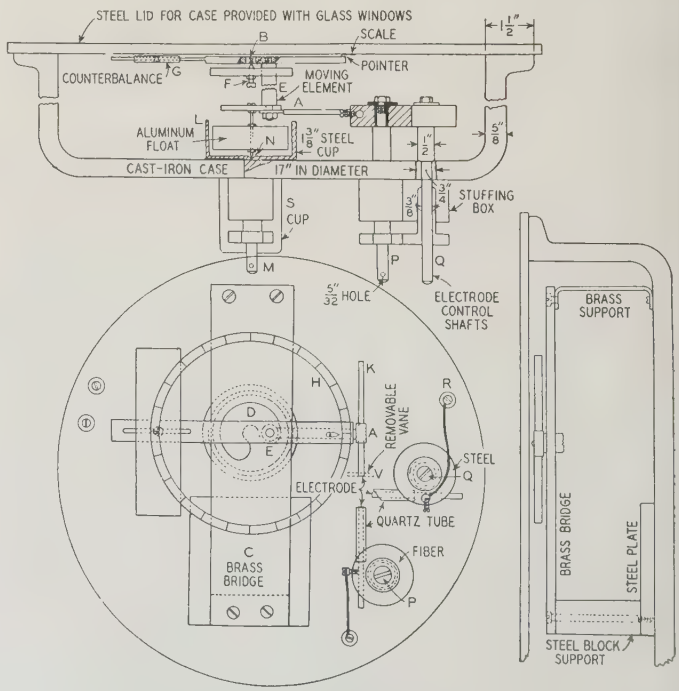


Fig. 1. Instrument used for measurement of impulses caused by high current arcs

ment used for the measurement of these impulses is a development of the idea of the Grassot fluxmeter, and gives a definite permanent reading for each observation. It is shown in Fig. 1. Here the diameter of the tank is 17 in. with the other parts drawn to scale. The tank is of cast iron, capable of being evacuated of gas, and containing an arm A mounted on a moving element pivoted at B and N. To A may be affixed an arcing electrode K or a quartz rod holding a glass vane V. B is a knife edge bearing mounted on the brass bridge C which also contains a hole D through which the shaft E of the moving element passes. Rod E connects the arm A and the aluminum float with an arm G which is equipped at one end with a counterweight and at the other with a pointer whose tip indicates the position of A on a scale H attached to the lid. In order to relieve pivot N of the weight of the moving element (about 1.25 lb) cup L is filled with mercury. The aluminum float is so proportioned that when the mercury completely covers its surface, the moving element rises slightly off the pivot N. A very small adjustable weight may then be added so that the moving element rests very gently on N, and it will be found that the whole instrument is almost completely free from static friction, no friction being left except the fluid friction between the float and the mercury. Since the mercury tank container is grounded onto the cast iron tank, an excellent electric circuit is provided for current passing through the electrode K. The fixed electrodes consist of 2 steel or fiber disks attached with appropriate insulation to the tops of the shafts P and Q. Terminals such as R are provided with flexible leads so that current may be led to electrodes clamped in the disks mounted on P and Q.

As shown in Fig. 1 the instrument is equipped with a vane V. The arc is struck by contacting electrodes P and Q. With this arrangement, forces due to particles projected from P onto the vane may be measured. If electrode Q and the vane V are removed, an arc may be struck between electrode P and K and the corresponding forces between these electrodes measured. In this case, however, difficulties arise in manipulating the arc. The instrument is far too sensitive to permit contact between K and P in order to start the arc. It is necessary therefore to arrange a high voltage discharge of 2,000 volts between P and K for this purpose. The arc having been struck with a current of say 5 amp (an operation not without difficulty since the high voltage arc in vacuum tends to go in any direction except the one desired) a further switch is closed so that a direct current of the desired value, which may be several hundred amperes, is caused to flow through the arc path for a fraction of a second, thus producing the impulse desired. A similar switching circuit is shown in the paper previously referred to (A.I.E.E. TRANS., v. 51, 1932, p. 556–63).

With either method of operation, that is, with vane V or electrode K, the energy imparted by the impulse to the moving system causes it to rotate (the arm A being repelled) until this energy has been absorbed by the fluid friction of the mercury on the float. Thus the number of degrees through which the pointer turns may be used as a measure of the impulse. It will be noted that the instrument has no spring or other control and therefore comes to rest when its energy is dissipated, and a reading may be taken at leisure. The moving element may be returned to zero position by turning the shaft M; mercury friction causes the pointer to follow.

The instrument is calibrated by means of a pendulum (see Fig. 2), 2 readings being taken. In one the swing of the pendulum is so adjusted as to give a deflection slightly greater than that due to the arc which it is desired to measure, and in the other so as to give a deflection slightly less than that due to the arc. Knowing the dimensions of the apparatus, the value of the impulse corresponding to any angle θ can be readily calculated. A coefficient of restitution due to the bob not being perfectly elastic is, of course, taken into account. The instrument was mounted on a solid concrete base but nevertheless it was found necessary to calibrate after every reading in order to get accurate results. If this precaution is taken, however, it is found that the measurements are quite accurate, as shown by their reproducibility after several months.

Owing to the construction of the instrument, it was not possible to obtain an extremely high vacuum, values of pressure varying from 20 to 50 microns of mercury being the best obtainable, the usual values being between 40 and 50 microns. Careful studies will be presented in the following paragraphs of the effect of varying the vacuum, which seemed to show that a further increase of vacuum would produce no effect other than slight increase of the forces measured. No fundamental changes in the phenomena due to higher vacuum, therefore, seem to us likely.

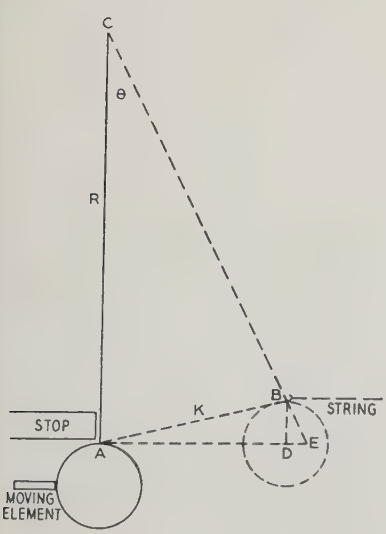


Fig. 2. Calibration pendulum

TESTS ON THE IRON ARC BETWEEN FIXED AND MOVING ELECTRODES

The method of adjusting the instrument to give accurate results was only gradually discovered as the result of experiments in its use. The curves of Figs. 3, 4, and 5 were among the first obtained. Nevertheless they have been included because they are suitable for the qualitative indication of certain interest-

Table I—Summary

Electrode Material		Average Current Amperes	Average Pressure Microns	R.M.S. Velocity in Cm/Sec: Cosine Dist.	R.M.S. Velocity in Cm/Sec: Maxwellian Dist.	Observer
Cathode Stream Summary						
Copper	(Cu)	11–32	0.2	6.73×10^5	1.04×10^6	*A*
		14–18	0.2	8.73×10^5	1.35×10^6	*A*
Copper	(Cu)	20	0.2	1.60×10^6	2.48×10^6	*B*
				1.32×10^6	2.04×10^6	*B*
Silver	(Ag)	166	.45	6.28×10^5	9.7×10^5	*C*
Aluminum	(Al)	110	.58	4.50×10^5	6.95×10^5	*C*
				1.19×10^6	1.84×10^6	*C*
Gold	(Au)	53	.90	2.63×10^5	4.06×10^5	*C*
Carbon	(C)	73	.42	2.32×10^6	3.58×10^6	*C*
				1.12×10^6	1.73×10^6	*C*
Cadmium	(Cd)	43	.66	1.06×10^5	1.64×10^5	*C*
Copper	(Cu)	115	.50	8.09×10^5	1.25×10^6	*C*
Iron	(Fe)	142	.50	5.70×10^6	8.80×10^5	*C*
Magnesium	(Mg)	55	.45	1.77×10^5	2.74×10^5	*C*
Molybdenum	(Mo)	135	.35	1.76×10^6	2.72×10^6	*C*
Tin	(Sn)	60	.61	0.77×10^5	1.19×10^5	*C*
Zinc	(Zn)	57	.56	3.44×10^5	5.31×10^5	*C*
Anode Stream Summary						
Copper	(Cu)	120	.50	8.22×10^5	1.27×10^6	*C*
Iron	(Fe)	106	.60	6.54×10^5	1.01×10^6	*C*
Tungsten	(W)	145	.40	7.68×10^5	1.19×10^6	*C*

Observer: *A*—Tanberg; *B*—Berkey and Mason; *C*—Easton, Lucas, and Creedy

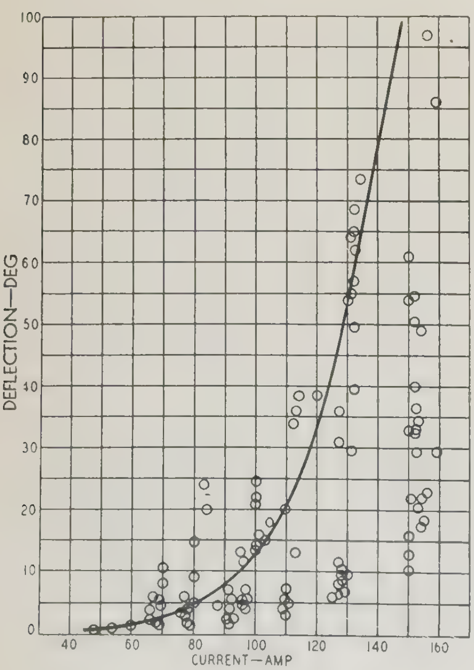
ing phenomena. Unfortunately, time did not permit a repetition of these tests after the instrument and the operating technique had been perfected.

It is shown in Fig. 3 that deflection of the instrument is independent of the arc length. Because of this, it was found possible to take observations at zero arc length, and thus, by touching the electrode tips together and throwing the high current on directly, to obviate the need of high potential for starting. In Figs. 4 and 5 the deflections produced by different currents are shown. In the tests leading to Figs. 3, 4, and 5, the pressure in the instrument corresponded to about 5 mm of mercury.

It must be emphasized that Figs. 4 and 5 show early observations of *deflection* against current. Separate calibration checks for each point were not made at this stage of the work. Therefore, a curve of *force* against current in which the scattering would be much less, has not been included. The curves drawn in these 2 figures pass through the upper limits of the observations since later tests showed that most of the low readings were caused by improper laboratory manipulation. These curves show the trend of the forces under consideration but are not to be considered as quantitatively correct. With this understanding we are entitled to make the following conclusions of a definite character.

1. Force is produced whether the anode or the cathode is stationary.

2. With the anode moving, the force is much smaller for low currents than with the cathode moving. Hence it is easily understood that the anode force might be overlooked if experiments were made with small currents only.



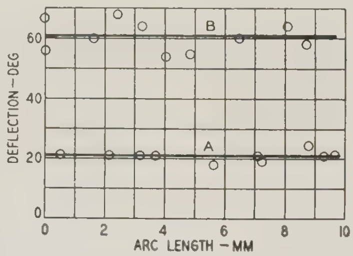


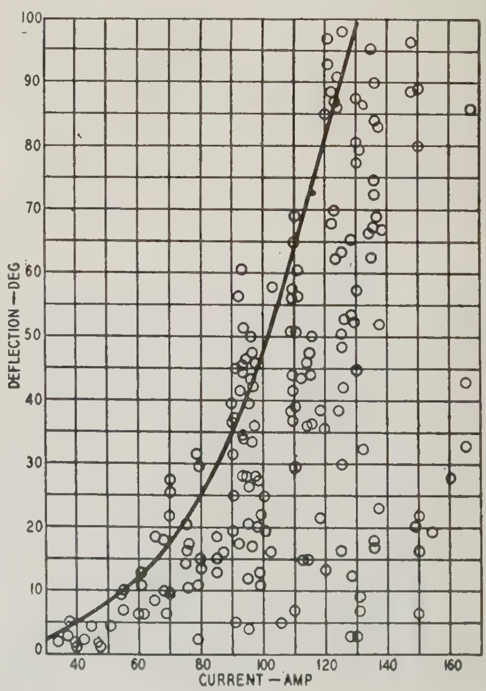
Fig. 3. Curves of deflection versus arc length with constant current

A. Moving electrode positive. 110 amp

B. Moving electrode negative. 150 amp

Fig. 4. Deflection versus current with moving electrode positive

Fig. 5. Current versus deflection with moving electrode negative



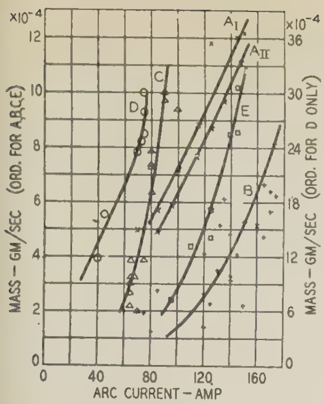
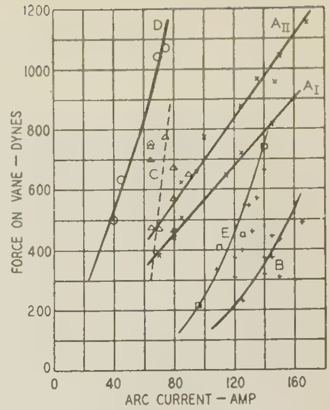


Fig. 6. Curves of current versus mass of metal condensed on vane. Constant pressure

A. Copper cathode. Pressure = 50 microns
B. Tungsten anode. Pressure = 40 microns
C. Carbon cathode. Pressure = 42 microns
D. Zinc cathode. Pressure = 56 microns
E. Copper anode. Pressure = 50 microns

Fig. 7. Curves of current versus force on vane. Constant pressure

A. Copper cathode. Pressure = 50 microns
B. Tungsten anode. Pressure = 40 microns
C. Carbon cathode. Pressure = 42 microns
D. Zinc cathode. Pressure = 56 microns
E. Copper anode. Pressure = 50 microns



3. With large currents the forces in the 2 cases are of quite the same order though not equal.

These conclusions are similar to those which might be reached after a consideration of the curves shown in the previous paper (A.I.E.E. Trans., v. 51, 1932, p. 556–63). In vacuum, however, the forces were much greater than those in air.

Tests on Velocity of Vapor Stream

After the apparatus had been improved, a number of tests were run to determine the velocity of the vapor stream emitted by electrodes of various metals. The tests on copper, iron, tungsten, carbon, and zinc were completed early in 1933. In the following pages they are described in detail. Several months later, other metals were investigated. Brief reports on these follow after the first series. The final curve (Fig. 11) shows all the cathode stream velocities, computed on the assumption of a Maxwellian velocity distribution, plotted against melting point of the electrode material. Table I shows at a glance the results of our work together with those of Tanberg and of Berkey and Mason. Our velocities are given in 2 values, one calculated on the assumption of a cosine distribution of normal velocity, and the other on the assumption of a Maxwellian velocity distribution. All velocities mentioned in the text are computed as with a Maxwellian distribution to facilitate comparison with the results of the others.

Under the assumption of a cosine distribution of normal velocity, the velocity is calculated from the formula

$$V = \frac{2\sqrt{2}}{\pi}\frac{K}{m} = 0.9\frac{K}{m}$$

where

K is the force against the vane in dynes
m is the mass of metal condensed in grams per second
V is the root mean square velocity (normal to the vane) of the particles in the arc stream in centimeters per second

The coefficient 0.9 is based upon the assumption that all arc particles proceed from the electrode, each with the same velocity; that they travel away from the electrode in all directions (but not with uniform distribution) so that particles leaving the electrode at any instant will lie on a hemisphere at a later instant; that they all travel in a straight path. The so-called Maxwellian distribution of velocity is obtained by substituting 1.39 for 0.9 in the above formula (R. Tanberg, *Phys. Rev.*, v. 35, 1930, p. 1080–9). This assumes that all directions of velocity are equally probable and that every particle has the same mass.

There will naturally be criticisms of any choice of distribution. Probably neither the cosine distribution nor the Maxwellian distribution is correct. Both results include the questionable assumption that all impinging particles adhere to the vane. Neither satisfactorily accounts for the effect of electric or magnetic fields on the particles. Neither makes any distinction between forces due to metal particles and forces due to gas given off by the electrode. In the absence of real knowledge as to the nature of the arc stream, the most important thing is to determine, if possible, a definite relation between the velocities of the streams between different metals, all calculated in only one way. Our results indicate a relation. They do not and cannot at the present state of our knowledge give an exact quantitative picture of the phenomena.

Tests on the Copper Arc

(Most of the conclusions of this section were derived by E. C. Easton.)

As in all tests concerning vapor stream velocity, a glass vane, substituted for the moving electrode K as described previously, was set up about 2 cm in front of the electrode P from which the vapor stream was to be emitted. The arc was struck by contact between P and Q (Fig. 1). The pressure in the tank during each test was measured on a McLeod gauge, while the mass of metal condensed on the vane was measured to 0.01 mg on a bullion balance.

A vapor stream was found to come from both the anode and the cathode, although the anode stream was not noticeable until currents of over 40 or 50 amp were used.

The following sections present curves of current against mass of condensed metal, current against force on vane, current against velocity of stream, and velocity of stream against pressure in the tank. It was not always possible to direct the vapor stream at the center of the vane, although, of course, an attempt was made to do so. Thus some variation both of the mass of the metal and of the observed force should be expected. It is obvious in all these

tests that it is impossible to be sure that all the force is due to the material deposited. Some material may drop off the vane before being weighed, and some force may be due to the emission of gas occluded in the electrodes. The results must always be read subject to this reserve.

The curves for copper are curves AI and AII in Figs. 6, 7, and 8, and curve A in Fig. 9. The copper arc was found to be considerably more stable than certain others and thus the curves for copper show less scattering than do similar curves for other materials where the arc could not be so readily manipulated owing to reduced stability.

Curves for Cathode Stream

Both the data for current against mass and current against force (curves AI and AII in Figs. 6 and 7), permit the drawing of 2 curves. Thus for current against mass 2 smooth curves can be drawn, each of which includes about half the observed points. Likewise there are 2 smooth curves for current against force. If the curves marked by the same Roman numeral, that is, I and I or II and II, be taken together, the resulting velocity curves (AI and AII, Fig. 8) pass directly through the observed velocity points. There are apparently 2 conditions under which the copper arc may exist, each condition being marked by a different velocity of the cathode stream. That the double curves are not due to variation in the position of the vane with respect to the arc is indicated by the fact that 2 distinct velocity curves appear. Were the possibility of 2 curves of current against mass merely a coincidence occasioned by variation in the position of the vane, there should have been, assuming only one arc condition, a corresponding disposition of the curves of current against force. In this case the lower mass curve would be taken with the lower force curve, and the 2 sets of curves would lead to the same velocity. In the actual tests, however, the observed velocities show that 2 conditions exist and that the lower mass curve must be considered with the higher force curve, and *vice versa*.

The curve of velocity against pressure (A, Fig. 9) taken at an average current of approximately 150 amp, shows that the velocity of the cathode stream

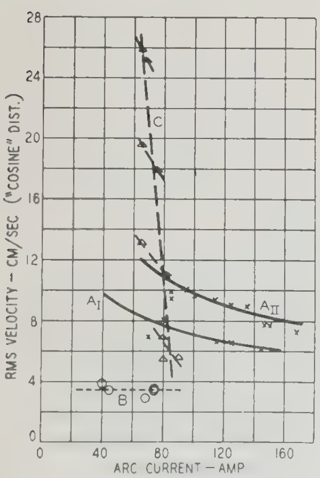
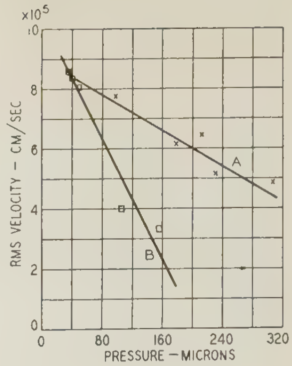


Fig. 8. Curves of current versus velocity. Constant pressure

A. Copper cathode. Pressure = 50 microns
B. Zinc cathode. Pressure = 56 microns
C. Carbon cathode. Pressure = 42 microns

Fig. 9. Curves of pressure versus velocity. "Cosine" distribution assumed

A. Copper cathode. 150 amp
B. Copper anode. 135 amp



decreases with increase in pressure. The data show that the mass of condensed metal varied very little with the pressure while the force on the vane fell off as the pressure increased.

By extrapolation to a current of 20 amp and a pressure of 0.2 micron, the values obtained for the velocity of the cathode stream are 2.41×10^6 and 3.48×10^6 cm per second. Working at a pressure of 0.2 micron and with currents ranging from 14 to 18 amp, Tanberg found a velocity of 1.35×10^6 while Berkey and Mason ("High-Velocity Vapor Stream in the Vacuum Arc" by R. C. Mason, A.I.E.E. Trans., v. 52, 1933, p. 245–8) working under the same conditions found a velocity of 2.48×10^6 cm per second. In these tests each investigator measured the velocity by the method of force on the vane, essentially the same method as used in our work. By different methods these same investigators found velocities of 1.04×10^6 and 2.04×10^6 cm per second, respectively. Using the force on vane method, Berkey and Mason report that their observed velocities ranged from 1.62 to 3.7×10^6 cm per second "with not very great accuracy." It would be interesting to know whether their scattered points could not have been better combined into 2 distinct velocities. It would also be worth while to know the range of variation in Tanberg's work. All these results seem to indicate 2 conditions of stability in the copper arc. However, because of the great difficulty of making accurate measurements, and because of failure to find a definite indication of a similar state of affairs in a few tests on arcs of other metals, we do not feel justified in announcing definitely the discovery of 2 possible conditions of stability.

If the velocities observed over a current range of 80 to 160 amp be averaged, a velocity of 1.25×10^6 cm per second at 50 microns is obtained. If this velocity be translated to a pressure of 0.2 micron it becomes 1.29×10^6, close to Tanberg's value of 1.35×10^6.

Curves for Anode Stream

A discovery of considerable interest brought out by this investigation is that a high speed vapor stream is emitted from the anode. All previous arc theory has denied the possibility of such a condition.

With the anode, the condition of dual stability was not observed, although the small number of points taken does not constitute the basis for any

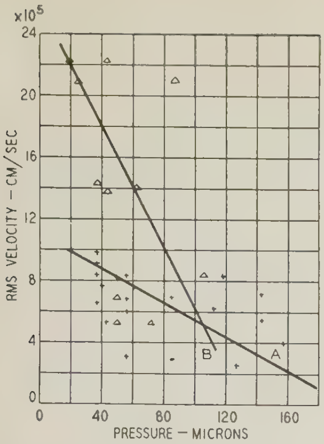


Fig. 10. Curves of pressure versus velocity. "Cosine" distribution assumed

A. Tungsten anode
B. Carbon cathode. 73 amp

definite conclusions. The velocities observed were apparently independent of the current, and had a mean value of 1.27×10^6 cm per second at a pressure of 50 microns. Curves of current against force and mass as well as of pressure against velocity are given in curves E of Figs. 6 and 7, and B of Fig. 9.

Inspection of the electrodes showed that while some change in the shape of the ends had taken place, there was very little boiling of either electrode. In all experiments the quartz tube surrounding electrode Q (Fig. 1) was so proportioned as to screen the vane from any particles which that electrode might emit.

The curve of force against current shows that for low current values the force is almost unobservable. Future investigators of this phenomenon will have to resort either to much more sensitive measuring devices or to large currents and short time intervals if this vapor stream is to be studied accurately.

Tests on the Tungsten Arc

The electrodes used in the tungsten tests consisted of a bundle of 5 $^1/_{16}$ in. pure tungsten rods held in place in a piece of Vitreosil tubing. When both electrodes were of tungsten it was found impossible to strike the arc in a vacuum. Because of difficulties in striking the arc satisfactorily even with anodes of other materials, tests on the tungsten arc were limited to a study of the anode stream using a tungsten anode and copper cathode.

In order to make sure that none of the cathode material was striking the vane, a chemical analysis was made of the metal condensed on the vane. The analysis showed that copper was not present.

Curves of current against force and mass as well as of velocity and pressure are shown in B of Figs. 6 and 7 and A of Fig. 10. The curves of current against force and mass show the velocity to be independent of the current. The mean velocity of the anode stream is 1.19×10^6 cm per second at a pressure of 40 microns and average current of 145 amp. The velocity diminishes with increase in pressure.

Tests on the Carbon Arc

Because of lack of time, tests on the carbon arc were limited to a study of the cathode stream. The electrodes used were 0.25-in. solid carbon arc-lamp electrodes. The various curves are shown as C in Figs. 6, 7, and 8, and B in Fig. 10.

The observed velocities varied from 8.5×10^5 to 4.0×10^6 cm per second at a pressure of 42 microns within a current range of 60 to 80 amp. At an average current of 73 amp the observed velocities appeared to be divided into 2 groups. Taking the average of each of these groups the 2 values 1.73×10^6 and 3.58×10^6 cm per second are obtained. These are the 2 values for carbon shown on Fig. 11. Apparently there may be at least 2 conditions of stability with carbon. The velocity apparently decreased as the pressure rose but the observed points are so scattered that no definite slope can be assigned to the curve.

Tests on the Iron Arc

Tests on the iron arc were conducted with electrodes made up of a bundle of 4 $^1/_8$-in. iron rods held in Vitreosil tubing. The rods were of pure iron (kindly supplied by Prof. G. E. Doan) with a gas content of approximately 0.07 per cent oxygen, 0.001 per cent hydrogen and no nitrogen.

Cathode Stream Tests

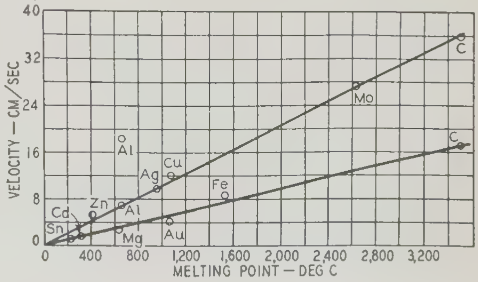
The observations with iron are very much scattered and therefore curves have not been included. The variation in velocity from 5.41×10^5 to 1.05×10^6 cm per second in a current range of 120 to 160 amp suggests the possibility of several conditions of stability. A few readings at high pressures indicate that the velocity decreases with rise in pressure. At an average current of 142 amp and pressure of 50 microns, the weighted mean of the velocity of the cathode stream is 8.8×10^5 cm per second.

Anode Stream Tests

A few points taken with the anode stream showed a velocity variation between 1.47×10^5 and 1.19×10^6 cm per second at an average pressure of 60 microns and current of 106 amp. Most of the points lay between 7.91×10^5 and 1.19×10^6. Discounting the other observations, the average velocity under the stated conditions is 1.01×10^6. Because of the few points taken, no curves are given for the anode stream.

It is interesting to note that the first 3 readings taken on the anode stream were smaller than those which followed. The same phenomenon was ob-

Fig. 11. Curves of cathode stream velocity versus melting point. Maxwellian velocity distribution assumed



served in connection with the first few readings on the cathode stream. It appears as though the electrodes must form in some way which alters the velocity of the emitted stream. The electrode formed as the cathode apparently had to be reformed when used as anode.

The pure iron arc was difficult to strike in vacuum, a starting current of 35 amp being necessary. This high starting current probably introduced some error due to the condensation of metal from the starting arc which was not included in the timing of the actual high current shot.

Cathode Stream Tests on Zinc Electrodes

The electrodes used were 0.25-in. chemically pure zinc rods. Tests on the cathode stream indicated the necessity of "formation of the electrode." Although the electrode from which the stream was emitted had been in use as anode and was not touched when the polarity was shifted, the first 2 velocities observed from the cathode were lower than any which followed. The mass of condensed metal was relatively larger for the first 2 shots. The results are shown in *D* of Figs. 6 and 7 and *B* of Fig. 8.

The velocity for a fixed pressure appears to be constant, no double condition of stability being apparent. The average velocity at a pressure of 56 microns and current of 57 amp is 5.31×10^5 cm per second.

Later Tests on Other Metals

Tests were later conducted to determine the velocity of the vapor stream emitted from the cathode of an arc between electrodes of the following metals: molybdenum, aluminum, silver, tin, cadmium, gold, and magnesium. The electrodes varied in form as follows: molybdenum, bundle of 3 $^1/_8$-in. rods; silver, 0.25-in. rod; tin and cadmium, $^3/_{16}$-in. rods; gold, roll of $^1/_{32}$-in. sheet about $^3/_{16}$-in. diameter; magnesium, bundle of several thin strips about $^3/_{16}$-in. thick.

These experiments brought into relief some possibilities of error in earlier experiments which had not previously been considered. Tests on the cathode stream using low melting point metals showed that a large amount of vapor surrounds the vane, as ample deposits were observed on the back of the vane holder and on portions of the tank shielded from the direct stream from either electrode. The discovery of this large amount of vapor in the region of the vane led to the conclusion that a Maxwellian velocity distribution would be more fitting than our previously assumed cosine distribution of normal velocity. With copper, which gave off little vapor, the deposit on the vane was seen to be strongest at the center while none appeared on the back of the vane. This led to the adoption of a cosine distribution. The subsequent tests showing metal on the rear of the vane indicate that a cosine distribution which permits velocities in one direction only cannot be entirely correct, and suggest the Maxwellian distribution. There is good reason to question the existence of this distribution but it seems more correct for the pressures at which we worked than the cosine distribution.

In an attempt to measure the cathode stream velocity of tungsten, a cadmium anode was used with a tungsten cathode. With this arrangement the arc struck easily. The deposit on the vane was, however, found to be almost entirely cadmium which had come from the shielded anode. Apparently, then, especially with low melting point metals, the weight of condensed metal used in all the velocity calculations must have been slightly excessive due to condensation of metal from the shielded electrode. This means that all our velocity readings are somewhat low, the error being greater the greater the relative amount of metal vapor permeating the region of the vane.

On the accompanying curves of cathode stream velocity against melting point of the cathode material (Fig. 11) the metals seem to be divided, those which gave off relatively large deposits lying on the lower curve. Zinc, however, lies on the upper curve although it gave off large amounts of vapor. So far all attempts to show that all points should fall on one curve have failed. It will be noticed that 2 points are given for aluminum. The 2 values represent observations on 2 different samples. A bundle of 3 $^1/_8$-in. rods of pure aluminum gave a velocity of 1.84×10^6 cm per second while a 0.25-in. rod of aluminum wire of unknown composition gave 6.95×10^5.

The phenomenon of decreasing velocity with increasing pressure is probably due to a change in the velocity distribution, the directions of the velocities at the vane becoming more haphazard as the pressure increases (assuming the arc particles to be of the size of molecules). Only a few readings were taken on each of the metals tested. The velocities herewith presented may be somewhat in error for that reason.

The conclusion reached from these observations is that the velocity of the cathode stream may be proportional to the melting point of the cathode material, this conclusion being, of course, drawn with reserve due to the known possibilities of error and difficulty of obtaining accurate results.

A check test on the copper electrodes used in the earlier tests gave a cathode stream velocity in the range of those observed several months previously and thus showed that our apparatus gave fairly consistent results.

Thermal Origin Indicated

Reviewing the evidence it seems that a thermal origin for these streams of particles is irresistibly indicated rather than an electric mechanism of the type suggested by K. T. Compton and others. The belief in a thermal origin is chiefly supported by the fact that these streams of particles come both from the cathode and the anode. It has been suggested that at a sufficiently high vacuum the anode spot would become so large that the anode would no longer be heated and the stream of particles would therefore cease. If this should prove to be the fact, it would of course only strengthen the belief that these phenomena are of thermal origin.

Diesel Electric Rail Cars and Locomotives

Gasoline and Diesel electric equipment used for motive power on rail cars and locomotives is considered in this paper. The more important problems such as the securing of a suitable method of drive for Diesel electric locomotives are considered, especially for heavy railway work. A comparison of Diesel electric with steam and with electric locomotives is given, and possible future developments are indicated.

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THE internal combustion engine has become a tremendous factor in the everyday life of the American people. With more than 26,000,000 automobiles in this country alone, to say nothing of the streams of trucks and buses which are found on the highways, the sum total of the potential power of these small gasoline engines is at least 10 times that of all the steam locomotives in the country. Little wonder then that the railroads feel the competition, for all of these engines are used in transportation work of one kind or another.

With the gasoline engine constantly before them, the Diesel engine making progress with the cheap fuel oils, and the success the railroads have had with both the gas and Diesel rail cars and locomotives, it is natural that the executives should look to these same agencies to help them out of their difficulties still further. We are apparently on the verge of a large development in this field.

The use of gasoline engines on the railroads for light cars dates back to the early part of this century. Quite a number of cars with mechanical drive were built for local service on Western railways. A number of others were built with electric drive, but the cost of gasoline and other factors were such as practically to stop the development before the war broke out. After the war, however, it began again with renewed vigor, first with modified gasoline buses adapted for running on rails. These, of course, had the standard automobile or truck type of drive. They gradually grew into the standard railway type of passenger car, first with mechanical drive, then as the size of engines increased, with electric drive, which is now practically universal.

Full text of a paper presented before the Institute's Cleveland, Ohio, Section, March 13, 1934, and recommended for publication by the A.I.E.E. committee on transportation. Manuscript submitted Apr. 25, 1934; released for publication May 31, 1934. *Not published in pamphlet form.*

Widespread Use on Rail Cars and Locomotives

The use of gasoline and Diesel electric rail cars has grown to quite large proportions, considering the times. There is scarcely a railroad of any size that has not one or more in service. The engine has grown from the early beginnings with 75 or 100 hp until there are now cars in operation with 800 or even 900-hp engine capacity, either with single or double power plants. The latest development, of course, is the high speed streamlined train that is expected to revolutionize rail passenger service. This is at present in more or less of an experimental stage and there is no telling how far its influence will extend, but the interest displayed in it and the number of trains built and on order insure that it will have a thorough tryout. It seems to be the refutation of the old idea that the Diesel engine is good for slow or possibly moderate speeds but too heavy for high speeds.

The Diesel engine is making rapid progress in locomotives as well as in rail cars. It has won a very strong position in switching service with engines of 300-hp to 800-hp capacity. Few locomotives of larger than 1,000 hp have thus far been built. The Canadian National locomotive with articulated cabs, each with one 1,330-hp high speed Diesel engine, is still the largest built, but it will not be long now until larger locomotives driven by Diesel engines will have been constructed.

Problems in Application for Heavy Railroad Work

There are many problems connected with the use of internal combustion engines for heavy railroad work:

1. *The Engine.* The engines must be developed in large enough units, of small enough dimensions, light enough, reliable and satisfactory in every way so that the locomotives driven by them will have advantages that will outweigh the increased cost over steam locomotives. The question of engine design, however, will not be taken up in this paper as it is a very large subject in itself, which is being ably handled by engine builders.

2. *The Drive.* The perfect engine may be designed and built, but it is of little use in a locomotive without a satisfactory means of transmitting the engine torque to the driving wheels. The electric drive with a generator driven by the engine furnishing current with variable voltage to electric motors geared to the drivers, is generally accepted as the best system that can be devised, but some engineers see in it a round-about and inefficient way of getting the power to the wheels. They yearn for what seems to be a more simple means such as some unknown mechanical drive. This has been fairly well discussed many times before, but at the risk of being tiresome will be considered briefly in this paper.

3. *Control.* The engine may be perfect, and the generator and motors 100 per cent good, but the locomotive will not be up to its possibilities until it is equipped with a control system that will not only be perfectly smooth in its application of power to the locomotive, but will whenever it is needed utilize every bit of power the engine can develop without overloading it.

4. *Auxiliaries.* There are many auxiliaries on a locomotive that are of vital importance in the performance of the locomotive, many of which require power for various purposes: engine starting, air compressors, blowers or fans for cooling radiators for engine oil and

water, blowers for cooling motors on large locomotives, and pumps for oil and water. Power for all these purposes should be furnished by the engine, which is the sole source of power. Passenger locomotives will probably also have a boiler for train heating which may, as in the case of the one on the Canadian National Railroad, be equipped with an economizer to save the heat in the waste gases from the engine.

The Drive

A typical speed-tractive effort curve for 2 1,500-hp Diesel driven locomotives is shown in Fig. 1. The first is a curve or series of straight lines connected together, marked 1, showing the speed and tractive effort for a 1,500-hp engine with a 4-speed mechanical drive; and second, a curve marked 2, showing the speed-tractive effort that would be developed with the best electric drive. There is also a curve showing the full output of the engine translated into speed and tractive effort with 100 per cent efficiency. Comparison between this curve and the ones below it, shows the loss in power due to the drive either by inefficiency or by inability to run the engine at full speed.

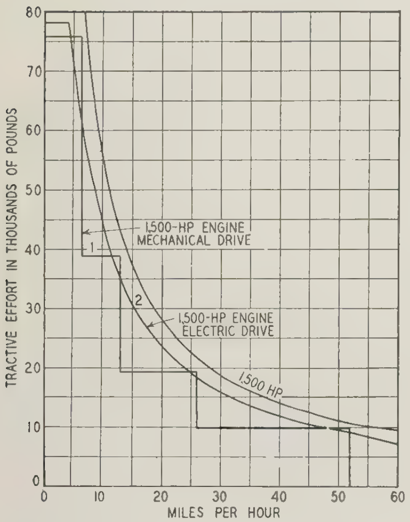

Fig. 1. Comparative performance of Diesel engine locomotives with different drives

1. 4-speed mechanical drive
2. Electric drive

The efficiency of the mechanical drive is assumed to be 85 per cent at the low gear, 88 per cent on the second, and 90 per cent on the 2 higher speeds. Considering the fact that a clutch, one or more gear reductions, jack shaft and side rods will be necessary with this type of drive, it is felt that these efficiencies are liberal. The efficiency of the electric drive is calculated to be 60 per cent with maximum tractive effort, reaches a maximum of 85 per cent at about 20 mph, and holds that value over the remainder of the speed range. This efficiency is not up to the maximum assumed for the mechanical drive, but the average power available at the wheels is much greater, as will be seen in Fig. 2, which puts the same facts developed by Fig. 1 in a different form. This shows the horsepower available at the wheels over the entire range of speed, first with the 4-speed mechanical drive, and second with the electric drive.

From this it will be noted that the average horsepower available over the range of speed from 10 mph up with the mechanical drive is about 1,000 hp, while with the electric drive it is about 1,250 hp, the electric being at least 25 per cent higher than the mechanical drive. This shows plainly that to have the same average horsepower available at the wheels with a mechanical drive would require an engine 25 per cent larger than with the electric drive. Even then the control would not be smooth with a single engine, as power would have to be cut off while changing from one gear ratio to another; this has inevitably in the past been productive of broken couplings, etc. It is essential, therefore that there be at least 2 engine units so as to maintain a drawbar pull at all times by changing one at a time. This is a time waster.

The question of clutches is also very important. The best clutch is, of course, an electric clutch, but even with the advantage of that clutch it is hard to see how the Diesel powered locomotive can be particularly successful with mechanical drive with the huge engines that are required. With a solid connection between motor shaft and driving axles the whole system would be subject to severe shocks. The engine could seldom be worked up to its full torque without danger of stalling it, since its torque would have to equal or excel the requirements of the train at all times. The foregoing shows clearly the necessity for a larger engine if a geared mechanical drive is used. A hydraulic or some efficient drive with a large number of speed ratios might change the picture somewhat.

Comparison of Diesel Electric With Steam Locomotive

It is interesting to study the Diesel electric locomotive in comparison with one driven by steam. An excellent analysis of this is given by A. H. Candee in "Performance of Diesel Locomotives," an article in the *Railway Age*, Dec. 2, 1933, p. 789–90. In this article is compared the performance in switching service of a steam locomotive with an output of 1,220 hp and a weight on drivers of 111 tons, with a Diesel electric locomotive with an engine capacity of 800 hp and a weight on drivers of 115 tons. The Diesel electric locomotive has a higher tractive effort at low speeds due in part to the heavier weight on drivers but much more to its uniform torque as compared to the pulsating torque of the steam locomotive. The curves shown indicate that the Diesel electric has a decided advantage in acceleration due to this fact, which enables it to gain distance up to a speed of 8 or 10 mph. It is therefore well ahead when those speeds are reached. The speed curves show that the 2 locomotives will give equal performance for runs varying from 740 ft with a load of 500 tons to 1,620 ft with a load of 2,000 tons. Above those distances the advantage is with the steam locomotive. On shorter runs the advantage is with the Diesel electric locomotive. To equal the performance on longer runs the Diesel electric locomotive should have the same horsepower available at the wheels as the steam locomotive.

Comparison of Diesel Electric With Electric Locomotives

In connection with this subject, it may be well to mention the idea, which has gained some ground, that the development of the Diesel electric locomotive will put a damper on the progress of the electrification of railways. The contrary is likely to be the case. The introduction of Diesel electric locomotives on steam railroads will educate the operators in the advantages of electric propulsion. There will be no quarrel between the straight electric and the Diesel electric locomotive. Each will be applied in the place where it is most economical. Regarding the advantage of the electric over the Diesel electric locomotive in heavy service, Fig. 3 shows comparative curves of the 1,500-hp Diesel electric locomotive indicated in Figs. 1 and 2, and a trolley fed electric locomotive equipped with identically the same motors as the Diesel electric locomotive. The electric locomotive will have the same maximum tractive effort and the same maximum speed as the Diesel electric, the only difference being that the maximum voltage is available on the trolley at all tractive efforts. The comparison is quite startling as it shows that at the maximum tractive effort where the Diesel electric locomotive has a speed of 4.3 mph, the straight electric locomotive may reach a speed of 21.25 mph—practically 5 times as great. With lower tractive efforts the speed of both locomotives increases, but while the Diesel electric locomotive speed increases at a more rapid rate, it does not reach the same speed as the electric locomotive until the tractive power has fallen from 78,000 lb down to 10,500 lb at 45 mph.

In Fig. 4 these curves are put in a different form, plotted in terms of horsepower and speed; this figure shows the maximum horsepower available on the electric locomotive to be about 4,400 at maximum tractive effort as compared with a maximum of 1,275 on the Diesel electric locomotive available from about 24 to 52 mph. The average horsepower of the electric locomotive is much larger and is good evidence of the advantage of having a central station with unlimited power back of the motors on the locomotive. It gives a much higher rate of acceleration and higher speed on grades than is possible with a constant or limited output locomotive.

Motor Capacity

The question naturally arises in one's mind on noticing such figures as just given, as to why it is necessary to equip the Diesel electric locomotive having only 1,500-hp capacity in the engine, with motors which are able to carry, even for a short time, a load of 4,400 hp. The answer is simple. The current capacity of the locomotive driving motors is fixed by the tractive effort required. The voltage is determined by the maximum speed required with full engine output. These 2 conditions, together with the range of speed over which the continuous load is required, are the ones which determine the size of the motor. Of course, the high voltage and the high currents are never applied to the motor simultaneously on the Diesel electric locomotive as they are with the trolley fed motors, but the weight of material is nearly as much as if they were to be so applied.

It is further desirable to have larger motors than are necessary to handle simply the engine output at one speed. The motors, in order to utilize the full output of the engine over a range of locomotive speed from the minimum to the maximum, should be large enough to carry this load continuously over a considerable portion of the speed range. For that reason it is customary with the Diesel electric locomotive to rate the motors at a voltage considerably below the maximum which they receive from the generator. In the case, for instance, of the locomotive for the Canadian National Railway equipped with 1,330-hp motors, the motors can carry the full tractive effort obtainable at 10 mph at their one-hour rating. They will operate continuously from 17.5 mph up to 50 mph with all the power the engine can give them. The increase in speed from 17.5 up to 26 mph is obtained by increasing the voltage of the generator. From 26 mph up to 50, the motors are operated at constant voltage but with weakened fields, there being several steps in shunting the fields.

With the Diesel electric where the power is limited to practically the rating of the engine, it is quite essential that the motors as well as the generator be of maximum efficiency so as to transmit the maximum percentage of power to the wheels. The size of copper in the windings of these motors and generators is of special importance when it comes to heavy loads. Since the copper loss increases as the square of the current, while the power input to

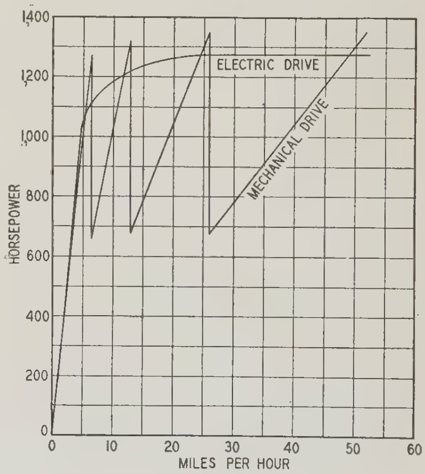

Fig. 2. Comparison of horsepower available at wheels with 1,500-hp Diesel engine locomotives, with different types of drive

1. 4-speed mechanical drive
2. Electric drive

the generator remains constant, the copper loss in percentage also increases as the square of the current.

Generator

The generator for a Diesel electric equipment is materially larger than one which would be used for the same engine located in a power house delivering current to a constant voltage network. The power house generator, for instance, would have as its

maximum current the amount necessary to give the output with the engine delivering its rated load and with a normal line voltage. The continuous rating would scarcely be more than 85 per cent of this maximum so that the rating of a generator in horsepower would be not more than 80 per cent of the engine rating. The generator for the locomotive, on the contrary, would be materially larger as it must be able to load the engine to its full rating over a considerable range of voltage besides carrying very heavy loads at starting. The generator in fact must be able to carry the current required for the motors which as has just been shown, are necessarily large for the engine capacity. Series-parallel control will make a material reduction in the generator capacity in a class of service such as switching or on cars where very frequent stops are made. Otherwise the generator must be able to carry the same currents that are supplied to the motor circuits.

Control

There have been a great many schemes of control suggested and tried on gas and Diesel electric cars and locomotives. The one fundamental aim of practically every engineer who has worked on the problem has been to obtain a simple equipment that will automatically load the engine to its full capacity over a wide range of car speed and tractive effort without danger of stalling it. Many ingenious schemes have been devised, all of which may be divided into 2 general types:

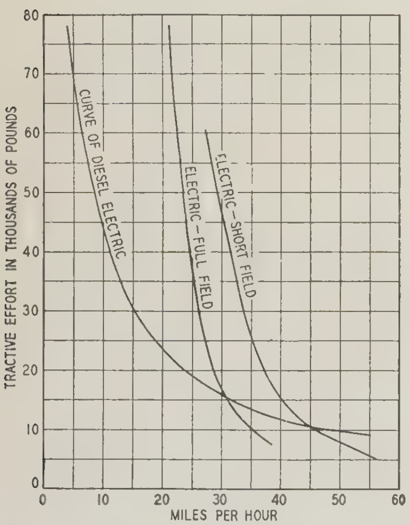

Fig. 3. Comparative performance of 1,500-hp Diesel electric locomotives and electric locomotives, both having identical motors

1. Those which rely on the inherent characteristics of the generator or generator and exciter; and,

2. Those which rely on minute variations of engine speed to make the generator torque conform to that of the engine.

Control Schemes Depending Upon Engine Characteristics

There are many schemes of the first kind. One of the best was described by N. L. Freeman in a paper "Control Systems for Oil and Gasoline Electric Locomotives and Cars," A.I.E.E. Trans., v. 49, 1930, p. 1262–8. This scheme uses a specially designed exciter with 2 of its 6 poles having a differential series winding so proportioned as to give the generator curve a very close approximation to that of the engine and thus load the engine to its full capacity while covering a considerable range of current and voltage. This is a simple scheme and so far as performance is concerned is quite satisfactory in most respects. However, it does not and cannot load the engine under all conditions of temperature, altitude, and engine variations. There are many variables which affect the output of a gasoline or Diesel engine. If any of these limits the torque, the engine will slow down and its output will be correspondingly reduced. When the windings of the generator are cold the generator will be loaded to a much higher torque at any given speed and current, which, in turn, will pull down the speed even if the engine is in perfect condition. These are well known characteristics of any scheme depending upon inherent regulation of the generator and exciter for loading the engine. Some schemes such as the one described, have characteristics which reduce the load very rapidly as the speed falls, so as to acquire a balance with a relatively small reduction in speed, but they can never develop the maximum horsepower-hours from the engine in a given time.

Torque Control Scheme

In the same paper, Mr. Freeman described the best known scheme of the second type, the "engine torque control" system. This depends upon variations in engine speed from its fixed rate to furnish the regulating impulses that make the torque required by the generator conform to that developed by the engine.

In the torque control scheme, the slightest decrease in speed, no matter what the torque of the engine may be, results in an instantaneous reduction of load by the introduction of resistance in the field circuit. On the contrary, an increase in speed cuts the resistance out of the circuit. The scheme adopted works very quickly, and the resistance is cut into the circuit and out again very rapidly so that the speed is maintained at whatever point is desired. It can readily be seen that this scheme will operate independently of the condition of the engine or the throttle opening. There are, of course, limits to its performance, but it has been known to work and maintain the speed of the engine even with 3 cylinders out of 6 cut out of service. This control will enable the generator to accept all that the engine can give it and transform it into current and voltage for the motors with its maximum efficiency.

Torque control is adapted to either throttle control of the engine or an engine with variable speed governor. The proper way to handle the throttle control is to select a certain number of speeds at which it is desirable to operate the engine. These will correspond to certain notches on the master controller. It is obvious that it is un-

necessary to operate at full speed when only a small amount of power is required, and the control can be adjusted so as to operate with the best throttle opening for each speed until the maximum throttle is reached. Then the loading above that speed will always be with maximum throttle, but with variations in speed, if desired.

The way to control an engine with a variable speed governor is to load the generator so as to keep the speed slightly below that for which the engine governor is set. The governor will then keep the throttle open as long as the generator is able to load the engine. Only when the maximum voltage has been reached and the load falls off will the governor act to cut down the throttle opening. Whenever the controller is moved to a higher speed notch, the load on the generator is momentarily decreased, which allows part of the engine torque to be used to accelerate the engine to the higher speed. The instant that is reached, the load is applied in full, and the generator again takes all that the engine can give it.

The apparatus required for this control is very simple, rugged and reliable and has been proved by several years of service. The auxiliary generator exciter is regulated for a constant voltage after it reaches a certain speed, say $^3/_4$ of the rated speed of the engine. A sensitive but very rugged relay is connected across the exciter terminals in series with a variable resistor. The slightest variation in speed affects this relay, which, if the speed has fallen, opens a contactor which inserts a resistor in the field circuit of the main generator. This, of course, lowers the voltage of the generator and consequently lowers the load, which restores the speed and the generator would run above the speed if the switch did not close again immediately. By a special connection which anticipates the change in speed, the contactor is kept vibrating at such a rate as to maintain the load constant over the full range of current and voltage until the motors can no longer use the load because of operating at maximum voltage and weakest field.

Auxiliary Operations With Torque Control

Corollary to this scheme are many possibilities for auxiliary operations. There is battery charging from a constant voltage circuit through a small resistor; also constant voltage available for operating compressor motor, blower motors, or even motors for such uses as air conditioning. The torque control also utilizes the main generator to furnish current for charging the battery and driving the auxiliary motors at idling, also as a motor for starting the engine from the battery, a scheme which has also been adapted to the differential system. It is uneconomical to design the auxiliary generator to cover the full range of speed but this is entirely unnecessary since the main generator can just as well furnish the low voltage current required at idling speed. No additional switches are required since the battery starting switches are simply closed when the idling speed is reached, and the starting series field acts as a differential winding which prevents excessive loading. With this equipment the following results are thus gained:

1. Perfect control of the generator loading to balance the power available from the engine at all times and speeds.

2. Engine starting from battery current through the main generator.

3. Constant voltage current from the auxiliary generator for battery charging and for auxiliary motors and field excitation during the operating speeds of the engine.

4. Current for battery charging and auxiliary motors from the main generator at idling speed.

The additional relay and contactor required over the control for a differential equipment are offset by cheaper exciter and main generator. The apparatus is all rugged and reliable. The principle of the scheme is right since it depends rather upon the torque and speed of the engine than on any inherent characteristics of generator and exciter which are not constant under all conditions. One point is worthy of mention in connection with the use of this scheme for large engines. With some of these machines, the auxiliary load is quite a considerable item and is not constant. The control adapts itself incidentally to permitting the auxiliary load to come off first, and of using whatever power is left in the engine to handle the train. This intermittent load such as a compressor gives, or the motor of an air conditioning equipment, would affect any scheme of differential control seriously and make it advisable to use a separate engine for operating the auxiliaries. It is unnecessary to go to such an expense and complication where the torque control system is used.

The idea seems to prevail in some quarters that the term "torque control" necessarily includes not only control of engine loading, but all the auxiliaries. Such is not the case. Directly driven auxiliaries may be used with torque control just the same as with any other system, and the battery may be charged enough in some classes of service such as switching, if charged only in idling from the main

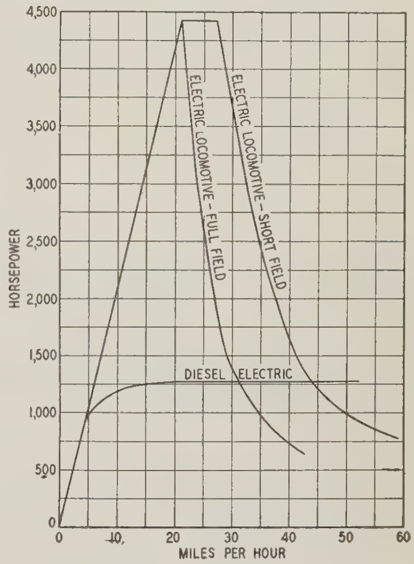

Fig. 4. Comparison of horsepower available at wheels with Diesel electric locomotives and electric locomotives

1. 1,500-hp Diesel electric locomotives
2. Same traction motors supplied from trolley

generator. This removes all load but the field current for the main generator from the auxiliary generator so that it becomes simply a small exciter. The control for auxiliaries is also eliminated from the electrical equipment. Therefore, before comparing this system with differential or self-excited generators, they should be put on the same basis so far as auxiliaries are concerned.

Future Possibilities

In conclusion, there is a great field ahead of the Diesel engine for railroad work unless some new development provides an engine that can do the work at a lower cost. The electrical manufacturers can furnish equipment for any size of Diesel engine that can be put on a locomotive or rail car. They can load it at all times so as to secure the most efficient use of the power available. Whether the railroads are to be electrified by Diesel electric or by central station power may be a question in the minds of some people. To anyone, however, who is familiar with the situation, the conclusion is inevitable that each one will have its own field. If, when, and as the manufacturers of Diesel engines can produce engines of 2,000 to 3,000 hp in single units, which will have a weight per horsepower of 10 to 20 lb, which will be efficient and reliable, and with dimensions suitable for mounting on a locomotive, there will be a great demand for Diesel electric locomotives, especially for lines with rather lean traffic where it would certainly be uneconomical to electrify. However, there seems to be scarcely any question or any room to doubt that it will be more economical to electrify railroads with heavy traffic than to operate them with Diesel electric locomotives.

Power Losses in Induction Machines

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Losses in induction machines have been subjected to a detailed study by many investigators, but due to the complex nature of some of these losses, particularly several forms of load loss in induction motors, a clear understanding of their nature has not been available. Since the majority of such losses are connected with the magnetic flux in the machine, a study of the distribution of magnetic flux in the stator and rotor is necessary; such a study is presented herewith. The flux losses considered are divided into 2 groups, those occurring at the fundamental frequency, and those occurring at tooth frequency.

IN THE study of the efficiency of electrical machines the knowledge of sources of power loss within the machine is imperative. Many excellent papers have been written, giving methods of determining and predetermining some particular forms of loss in induction machines, and making a substantial contribution to our knowledge of the subject. Some of the losses, however, are quite complex and do not readily yield to a mathematical treatment or to an experimental determination. This is particularly true in regard to some forms of load loss in induction motors. Before a quantitative analysis of these losses is made it is necessary to have a clear understanding of their nature. The object of this paper is to show the mechanism of various losses in induction machines, as determined from the works of various investigators.

All losses in induction machines, except friction, windage, and copper resistance loss, are intimately connected with the magnetic flux within the machine. It is obvious, therefore, that a detailed study of flux distribution is a logical way of approach to the study of the problem of losses. Caused by the changing flux, all losses can be conveniently classified into 2 groups: losses occurring at the fundamental frequency, and losses occurring at high, or tooth, frequency. Both of these groups involve a certain amount of iron losses (hysteresis and eddy current), and copper eddy-current losses. The paper will proceed with the discussion of the above 2 groups of losses taken separately.

Fundamental Frequency Losses

In the fundamental frequency losses there are included losses caused by the uniformly rotating main flux, and leakage fluxes in both rotor and stator, varying at the fundamental frequency. These losses occur at line frequency in the stator, and at

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slip frequency in the rotor. The diagram of Fig. 1 (a line reproduction of a photograph of a flow of liquid, taken by Dr. W. M. Thornton, see I.E.E. *Jl.*, v. 37, 1906, p. 125–37) gives an idea of the flux distribution in the air gap and the armature of an electric machine. As can be seen from the drawing, in any point of the magnetic circuit the flux may be considered as consisting of 2 components: a radial component, and a tangential component. The radial component in the teeth and slots constitutes the greatest percentage of the total flux in the region of the maximum flux density. This component is active in producing all useful currents and voltages in the induction motor windings. The tangential component constitutes the greatest percentage of the total flux in the region of a minimum air gap flux. Because of the presence of this tangential component, the flux in the teeth and slots never dies down to zero value while reversing in direction, but varies elliptically.

In order to see in what way the losses occur the truth of the following general statements will be noted: In any volume of a conducting or magnetic (or both) material, losses of energy will necessarily be caused by any change in the pattern of magnetic flux penetrating the volume, provided the hysteresis and resistance effects in the material are not zero. The reverse statement is also true, i. e., no loss can be caused in an insulated volume of any material by moving it in a magnetic field at a uniform speed, provided the flux pattern in the volume remains the same. The truth of these statements regarding a magnetic material can be readily seen if we remember that a hysteresis loss is caused only by a change in the magnetic state of the material, the change being either in intensity or the direction of the field. In a conducting material, the change in the flux pattern causes different electric potentials to be generated in different parts of the volume. These potentials produce eddy current losses within the volume. It will be seen that a moving flux of a constant space distribution is not capable of producing eddy currents within an insulated volume, because the rate of cutting the flux is the same in this case in all parts of the volume.

In the light of the foregoing statements it can be seen that both eddy current losses and hysteresis losses are produced in the machine iron, and eddy current losses in the copper conductors, because the flux pattern changes at the fundamental frequency

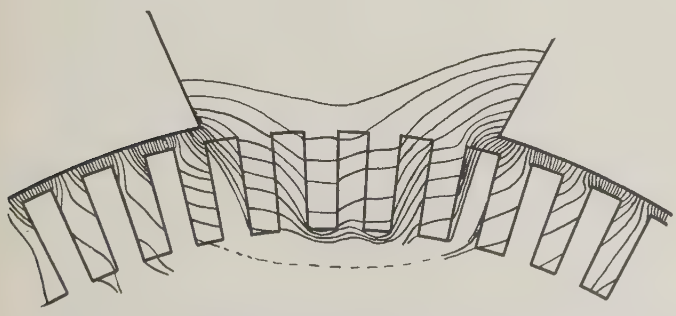


Fig. 1. Flux distribution in the air gap and in a part of armature of a salient pole machine

as the flux rotates. In regard to eddy currents in the conductors, it may be convenient to consider separately 2 mutually perpendicular components of flux: radial, and tangential. The cyclic variation in the radial component produces opposite potentials at the sides of conductors in the slots. Thus, the eddy current loss that is due to this mode of flux variation may be reduced by laminating the conductors in the radial direction. In a similar manner, the variation in the tangential component produces opposite potentials at the top and bottom of each conductor. The remedy is to laminate the conductors in the tangential direction.

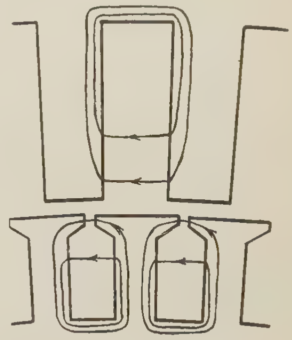


Fig. 2. Illustration of the leakage flux due to load currents

The losses described above occur at no load as well as at load. When the motor is loaded an additional fundamental frequency loss takes place. This loss is caused by leakage fluxes, as shown in Fig. 2. Surrounding each individual slot, this flux crosses the top of each slot in the tangential direction. While the current in the conductors reduces from maximum to zero value and the field disappears, the lower (internal) part of the slot is cut by a greater flux than the upper (outer) part, the difference between the 2 fluxes being equal to the flux crossing the slot when the field is a maximum. When no saturation in the iron is present, the losses caused by this leakage flux are proportional to the square of the load current, and, therefore, their effect is to increase the effective resistance of the circuit by a constant amount. With the stator or rotor slots closed by a thin iron bridge, the saturation in the latter increases the density of flux within the slot. This causes additional losses which appear with load, and which cannot be accounted for by adding a constant amount to the effective resistance of the circuit. With bar-wound stators these losses may reach a considerable value.

In low slip rotors, the fundamental frequency losses hardly amount to any appreciable value (disregarding the copper loss that is due to the main useful current), because of the low frequency of the loss producing fluxes. However, it must be pointed out that the leakage fluxes, being affected by the saturation in the iron, must have higher harmonics in them.

High Frequency Losses

Before proceeding with the discusson of the tooth frequency losses, a study of flux distribution disre-

garding the presence of copper conductors in the slots will be made. Eddy currents in these conductors set up their own fluxes, which change the flux distribution as determined by the shape of the magnetic circuit alone. This makes the problem of flux investigation more complicated.

Three modes of tooth frequency flux pulsation may be indicated which produce a certain amount of iron loss. They are:

1. Surface, or tooth tip pulsations.
2. Tooth flux pulsations (flux pulsations penetrating the whole length of a tooth).
3. Pulsations of flux in the core.

All these modes of flux pulsation constitute a variation of flux through a small cycle superimposed on the fundamental flux wave. As the cause of the flux pulsation is a pulsation of the permeance of the magnetic path, the amplitude of the high frequency pulsations depends upon the magnitude of the fundamental flux at the instant, i. e., it varies at the fundamental frequency. Considering the hysteresis pulsation loss alone, it must be pointed out that the hysteresis loop of the pulsating flux is, in general, unsymmetrical due to the presence of the fundamental flux. Furthermore, it has been shown[1] that, with an unsymmetrical hysteresis loop, the losses are relatively greater than with an ordinary symmetrical loop of the same flux amplitude. The eddy current loss caused by the high frequency flux variation shows also an effect unobserved under ordinary frequency conditions. Because of the skin effect in the iron, the eddy current loss increases less rapidly than the square of the frequency, for frequencies above 100 cycles. This influence of the skin effect relatively decreases the eddy current loss at the tooth frequency. It must be noted that, on the whole, the unsymmetrical hysteresis and the skin effect tend to equalize each other.

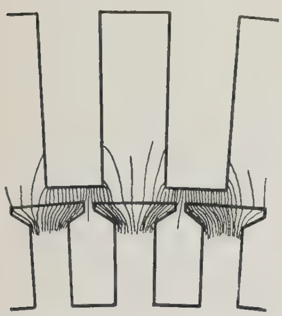


Fig. 3. Illustration of the tooth tip variation of flux density

Surface Flux Pulsations

Of the 3 manners of flux variation mentioned above, the first one is quite similar to the pole-face flux variation in salient pole machines that is due to passing teeth. It does not penetrate the whole length of the tooth, but disappears at a certain distance from the tooth tips. A rough illustration of this mode of flux variation is given in Fig. 3. It may be seen that the magnitude of the surface flux pulsations depends upon the fringing of flux in the air gap, i. e., upon the geometry of the magnetic path. Thus, the surface flux pulsations in the rotor increase with an increase in the width of the rotor tooth tip, but decrease with an increase in the air gap, because of the effect of flux fringing. At the same time a relatively narrower slot in the stator causes a smaller magnitude of surface flux pulsation in the rotor. With both stator and rotor slots closed, the flux pulsation is reduced to a minimum. With only the rotor slots closed (or semi-closed, as is commonly the practice), the surface flux pulsations in the stator are practically negligible, but may amount to a considerable value in the rotor.

Tooth Flux Pulsations

If an individual tooth is watched, whether in the stator or in the rotor, while the teeth of the opposite magnetic member are passing by, it will be noticed that the permeance of the magnetic path terminating in the tooth in question is oscillating through a definite cycle which repeats itself with every passing tooth. These oscillations of the permeance of a path terminating in a rotor tooth T are illustrated in Fig. 4; Fig. 4*a* shows a position of tooth T for the maximum permeance, whereas Fig. 4*b* shows its position for a minimum permeance. Since for a fixed average air-gap induction the magnetic potential between the rotor and the stator cores remains constant (it actually varies at a comparatively low fundamental frequency, disregarding the possible flux pulsations in the core), the variation in the permeance of the path of an individual tooth results in a similar variation of the tooth flux. This condition may be expressed algebraically as

$$\phi(R_t + R_a + R_s) = C$$

where the left hand member of the equation represents the total magnetomotive force in the cross-hatched path terminating in a single rotor tooth; ϕ is the magnetic flux in the tooth; and R_t, R_a, and R_s are the reluctances of the tooth, the air gap, and the stator teeth, respectively. Disregarding the effect of saturation, R_t is a constant, but, according to Fig. 4 $(R_a + R_s)$ oscillates at the tooth frequency. Obviously, ϕ must oscillate accordingly, in order to make the whole term constant. The magnitude of these flux pulsations depends upon the effect of slot fringing, i. e., depends upon the same factors as the surface losses. Since the fringing of flux increases with the saturation of the teeth, the tooth pulsations decrease with the saturation. Thus, the effect of the saturation of the teeth is to reduce the tooth pulsation losses. However, it should not be concluded from this that the tooth pulsation losses diminish with an increase of flux density in the teeth. It would be more accurate to say that the effect of saturation is to reduce the rate of increase of the tooth frequency losses, as the flux increases.

Pulsations of Flux in the Core

The arrangement of teeth in the stator and rotor may be such that the motion of the rotor causes

some tooth frequency variation in the total permeance of the magnetic circuit. With the ratio of rotor teeth to stator teeth markedly different from unity this variation, if any, is small, but when present it may cause the total mutual flux to pulsate. Actually, the pulsations in the total permeance of the magnetic circuit are more likely to manifest themselves as high frequency ripples in the magnetizing current than as an actual variation of the total flux. In either case, however, some loss is caused by the pulsation of the total permeance of the magnetic circuit. If this loss appears as the I^2R loss that is due to the high frequency component in the exciting current, the energy of the loss may be dissipated as heat, not necessarily within the motor, but in the line and the supply-generator conductors as well. But no matter where it be consumed, within the motor it will appear as a mechanical load on the rotor, and therefore it will always form a part of the input of the motor.

Copper Eddy Currents and Their Effect Upon the Flux Pulsations

So far an attempt has been made to describe the tooth frequency losses on the assumption that the copper conductors in the slots have no effect on the flux distribution. It is now intended to show the effect of the tooth flux pulsations upon the high frequency currents in the copper, and the mutual effect of these currents upon the magnetic flux. It has been shown experimentally[4] that the effect of the eddy currents is to reduce the amplitude of the flux pulsations, and, at the same time, to increase the power loss. Three kinds of high frequency flux pulsations which produce eddy currents in the copper conductors will now be considered in turn:

1. Pulsations of the slot leakage flux.
2. Pulsations of the tooth flux proper.
3. Pulsations of the fundamental leakage flux.

Effect of Slot Leakage Flux Pulsations

A sketch of the magnetic field of an induction motor showing the manner in which the slot leakage flux pulsates is given in Fig. 5. This drawing represents a rather typical open slot stator and a semiclosed slot rotor construction. Because of the small distance between the rotor tooth tips, the tooth pulsations in the stator are very small.

It may be convenient to consider the slot leakage flux as consisting of radial and tangential components. The amount of the radial component in the slot pattern obviously depends upon the position of the stator tooth relative to the rotor slot. When the stator tooth is directly opposite the rotor opening, the thin rotor tooth shoulders may become saturated easily, and a considerable part of the flux may penetrate the slot. Thus, at this relative position of the stator and rotor teeth the amount of the radial component of the tooth leakage flux is a maximum. When the stator and rotor teeth are in a position directly opposite each other, most of the flux passes through the teeth and only a small part penetrates the slot. Thus, at this position of the rotor and stator teeth, the radial component of the slot leakage flux is a minimum.

The tangential component of the slot leakage flux is generated in exactly the same manner as the tangential component of the fundamental frequency leakage flux. Whenever a flux density in any 2 adjacent teeth is different, the tips of the teeth are at different magnetic potentials, which causes some of the flux to cross the slot from one tooth to another. As the sign of the difference in flux density of any 2 neighboring rotor teeth varies twice during the time one rotor tooth moves one stator slot pitch, the direction of the tangential component in the slot between the teeth varies accordingly twice during that time. The pulsations of the tangential slot-leakage flux, together with the pulsations of the radial component, cause a part of the high frequency eddy currents.

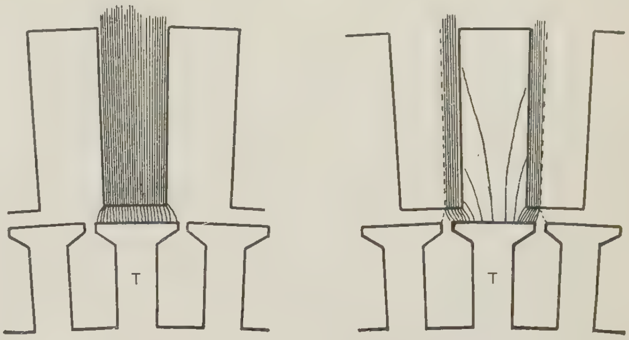


Fig. 4. Two relative positions of a rotor tooth T with respect to stator teeth, illustrating the variation of the permeance of the magnetic path which terminates in the rotor tooth

Effect of the Tooth Flux Pulsations

In a squirrel cage rotor the flux pulsation in the teeth is one of the causes of a circulating current in the short-circuited bars. Every 2 neighboring bars represent a closed low resistance electric circuit, which links with the magnetic flux in the tooth between the bars. High frequency pulsations of flux in the tooth induce high frequency pulsations in the bars, which in turn cause circulating currents. The effect of these currents is to set up fluxes of such a magnitude and direction as to oppose the flux variations producing the currents. The remaining flux pulsations in the teeth are just sufficient to induce voltage to overcome the resistance and the inductance of the bars. (An analogy is implied here between the electric curcuit in question, and a short-circuited low-voltage secondary of a transformer.) Since both the resistance and the leakage reactance of the bars are extremely low, the amplitude of the residual flux pulsations is very small.[4] Thus, at least as far as the squirrel cage rotor is concerned, the tooth frequency loss takes place not in the form of iron loss, but mostly in the form of copper resist-

4. For all numbered references see list at end of paper.

ance loss in the bar windings, due to eddy and circulating currents.

In a wound rotor, especially if the rotor conductors are comparatively small, the damping effect of the tooth frequency currents is not so pronounced as in a squirrel cage rotor, and the tooth frequency iron loss is probably an appreciable item.

Pulsation of the Main Leakage Flux

One more possible kind of high-frequency eddy-current loss is that due to the pulsations of the main leakage flux. It has been previously stated that the main leakage flux occurs principally in the form of a flux surrounding each individual slot, crossing the slot at the opening. As is shown in Fig. 6, a part of this leakage flux is likely to cross the air gap and to enter the opposite magnetic member (*e. g.*, rotor leakage flux may enter stator teeth). The leakage flux that crosses the air gap is commonly known as a zigzag leakage flux.

The reluctance of the path of the leakage flux which crosses the air gap depends upon the relative position of the stator and rotor teeth. When the teeth of one magnetic member are opposite slots of the other, the reluctance is a minimum. When the slots and teeth of the stator oppose the slots and teeth of the rotor, respectively, the reluctance is a maximum. This partial variation of the reluctance

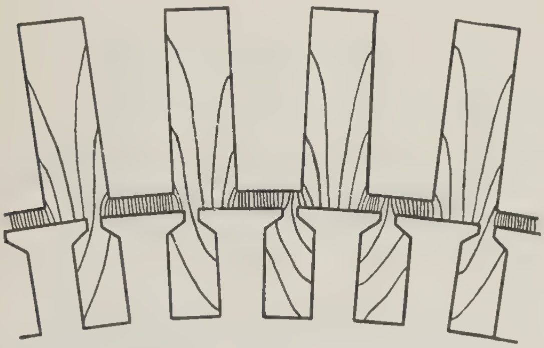


Fig. 5. Illustration of variation of slot leakage flux pattern caused by the relative position of rotor and stator teeth

may cause some pulsation in the magnitude of the leakage flux, and of the pattern of the flux in the slots. As the amount of leakage flux depends upon the load current in the conductors, the possible leakage-flux pulsation loss should vary approximately as the square of the load current.

Tooth Frequency Losses in the Stator

The above discussion of tooth pulsation phenomena was concerned mainly with the rotor of an induction motor. Flux pulsations in the stator present essentially the same features, although with the typical semiclosed (or closed) rotor slots, pulsations of flux in the stator are very small.

An interesting phenomenon must, however, be considered here: The damping of the rotor flux pulsations by the tooth frequency rotor currents increases markedly the pulsations of flux in the stator. H. Weichsel described this pehenomenon in a discussion appearing on p. 161–3 of the A.I.E.E. Transactions, v. 44, 1925. According to his description, the phenomenon was established by means of a search coil placed around a single stator tooth. The voltage induced in the coil was recorded, by means of an oscillograph, before and after the rotor windings were placed, with the rotor running at the same speed, and the same value of the excitation (impressed voltage) in both cases. The high frequency voltage was found to be increased greatly as a result of the damping currents in the squirrel cage winding. This observation is helpful in explaining the experimental fact that damping out the rotor flux pulsations by the eddy currents at the same time increases the total tooth frequency loss in the motor. If there is any decrease in the rotor

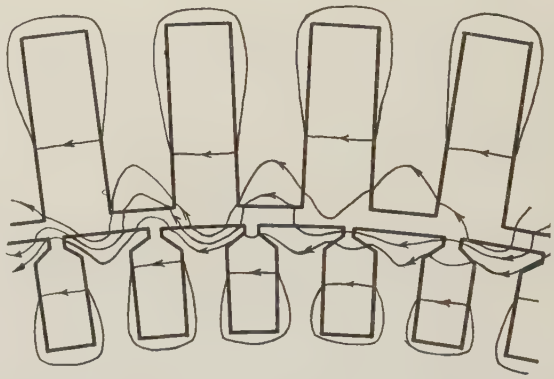


Fig. 6. Illustration of zigzag flux, and the effect of relative position of rotor and stator teeth upon the pattern of leakage flux in the slots

pulsation loss that is due to the damping currents this decrease is made up with excess by the increase in the stator tooth frequency loss.

Losses Due to Minor Fields

There are some minor losses in induction motors which have not been described above. Only 2 of them will be briefly mentioned here. One of these losses occurs in the end laminae of both rotor and stator, and is caused by the end-fringing of the main flux. An electromotive force induced by this fringing flux causes currents to flow in the plane of the end laminae, because, as the field changes its strength the lines of fringing flux cut the iron in a direction perpendicular to the planes of the laminae. This loss occurs at the fundamental frequency.

The other loss occurs in squirrel cage motors only, and is due to the nonsinusoidal flux distribution in the air gap. Ordinarily, the stator winding is placed in such a manner that the flux distribution only approaches a sine wave form (*e. g.*, it may have a trapezoidal shape). It may be shown that in this case the total air gap flux has irregular, high frequency components. When the air gap flux apparently moves at the synchronous speed of the

machine, only the true sine wave component participates in this motion, and is useful in producing the driving torque of the motor. The effect of the irregularities in flux distribution is to produce circulating currents in the squirrel cage bars, which increase the no-load loss, and make the flux wave more nearly sinusoidal.

Stray Load Losses

If the external causes of loss in induction motors are excluded, such as those caused by an unbalanced voltage, nonsinusoidal voltage wave, etc., the losses described above seem to cover all the possible modes of appreciable and nonproductive expenditure of energy within a machine. It seems to be logical, therefore, to look for the stray load losses, i. e., the additional losses appearing with load, among those previously described. In order to do this, it is necessary to see which of all the losses vary with the load, and in what manner.

First, it will be noted that some of the losses actually decrease with load. Consider, for instance, the manner in which the fundamental frequency flux changes with load. With a constant impressed voltage, the flux which links with the primary winding decreases slightly with load, because of the IR drop in the primary winding. This causes a slight decrease in the fundamental frequency iron loss.

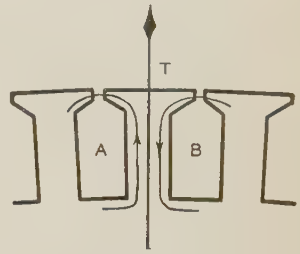
On the other hand, there are losses which definitely increase with the load. As the leakage flux is the only loss-affecting factor that changes with load, it must directly or indirectly account for the increase in the losses with load, i. e., it must account for the stray load loss. In the first place, the leakage flux produces a fundamental-frequency eddy-current loss in the rotor and stator conductors. With a bar-wound stator, this eddy current copper loss may reach an appreciable value. In rotor bars this loss hardly amounts to much, because of the low rotor frequency. In any case, the effect of this loss is to increase the effective copper resistance by a constant amount.

Furthermore, the leakage fluxes are likely to produce a high value of saturation in the tooth tips and, particularly, the thin tooth tip shoulders of semi-closed or closed slots. This saturation in the tooth shoulders causes a redistribution of flux in the air gap, and, what is more important, in the slots, every time the leakage flux exceeds a certain value. This occurs every half cycle. Accordingly, the load-leakage flux in the slots, when iron tooth tip shoulders get saturated, has pronounced higher harmonics in it. This increases the eddy current losses in the copper conductors that are due to the fundamental leakage flux, and may account for the fact, observed by some experimenters,[1] that machines which have closed slots in both rotor and stator show a high value of the stray load loss.

Other Contributing Factors

Another phenomenon that may contribute to the stray load loss is the tooth pulsation of the main leakage flux, illustrated in Fig. 6. Consider the extreme case of a closed slot rotor. At low load, when the rotor leakage flux is low, the iron bridges that close the slots are not likely to become saturated. Such being the case, the iron bridges represent a sufficient magnetic shielding against any effect of the stator teeth upon the distribution of the leakage flux in the rotor slots; i. e., no tooth pulsation of the rotor leakage flux is possible. When the motor is loaded, the rotor leakage flux assumes an appreciable value, the thin iron bridges become saturated easily, and the situation becomes as illustrated in Fig. 6, i. e., tooth pulsations appear in the leakage flux that crosses the slots. The eddy current power loss

Fig. 7. Illustrating the effect of leakage flux upon resultant flux in a rotor tooth



caused by these pulsations contributes to the stray load loss.

Within the stator and rotor teeth themselves, leakage flux may cause some distortion of the main flux. Figure 7 is intended to illustrate this point. Though the leakage flux that is due to the current in A is distributed through the cross section of tooth T, its density is not uniform throughout the cross section of the tooth, being greater near A and less near B. Similarly, the leakage flux density that is due to B is greater near B and less near A. If the direction of the main flux is as shown by the arrow, it is obvious that the resultant flux is of a greater density near A, and of a smaller density near B. Thus, the effect of the leakage fluxes within the teeth is to distort the resultant tooth flux, crowding it to one side of the teeth. This effect increases with load and may account for a part of the stray load losses.

As may be seen, the stray load loss in induction motors, whose satisfactory method of experimental determination is still a problem, is very likely a composite effect of several factors. The relative importance of these factors can hardly be discussed without further experimental investigations.

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A New Method of Ground Fault Protection

A new high-resistance "thyrite" and a new 3-element cold-cathode tube having unusual characteristics constitute the basic elements in a new high voltage relay combination for relaying or detecting ground faults on ungrounded systems. This scheme of protection, as described herein, is characterized by its reliability, simplicity, sensitivity, and low cost. It has been found to be particularly valuable in network applications.

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A GROUND fault which involves considerable current may be isolated by means of phase-current relays. If the ground fault does not draw appreciable current, its isolation becomes a problem.

A new relay combination has been developed for ground fault protection on ungrounded or delta-connected lines or on lines which may become ungrounded incident to the opening of one end. The relay scheme has been made possible by the development of a new "thyrite" resistor having extremely high resistivity and a new 3-electrode cold-cathode gas-filled electronic tube of unusual characteristics. ("Thyrite" indicates a resistor having an inverse nonlinear voltage-current characteristic.)

The development of the new method of ground fault protection and of the necessary devices was initiated as a result of the need for this type of equipment on ungrounded tie-lines and feeders. A particularly urgent need for such equipment has been evidenced on both primary and secondary network high voltage feeders. The application of the scheme to secondary networks is of considerable importance because it not only provides ground fault protection but it also performs an important function in the network operation as well.

To illustrate a general class of applications, consider the typical case of the ungrounded line section in Fig. 1. Here is shown a line section with a power source at each end feeding the line through delta-connected transformer windings. A large number of such line sections are in operation at various voltages among the various power systems of the country, and very few of them have any provision for ground fault protection. A ground fault on a line of this type displaces the voltage but does not draw any appreciable current.

Now consider another example: In Fig. 2 is shown a line section with a grounded source of power at A and an ungrounded source at B. Source A might be a grounded transformer bank as shown or it might be a grounded wye connected generator. In either case a ground fault at F will draw current from A sufficient to operate current relays to open circuit breaker B_a; but after breaker B_a opens, the current flow ceases and breaker B_b remains closed. The type of line section shown in Fig. 2 is universally used as a feeder for secondary networks, and in some cases, as a feeder for primary networks.

In this paper are presented an explanation and description of the new ground-fault protective scheme and associated devices, a discussion of their operating characteristics, and a discussion of the specific applications of which the above 2 cases are general classifications.

General Requirements

Before discussing the relay and its various applications, it seems pertinent to state the general specifications which a relay combination of the type under consideration must have. Since the application is a broad one, the requirements are necessarily severe. Specifically, they are:

1. The relay combination must depend only upon voltage displacement incident to a ground fault for its operation, since voltage displacement is the only appreciable change in the electrical system for this particular type of fault.
2. The general scheme must be applicable to all system voltages.
3. The equipment and its operation must be thoroughly reliable.
4. Correct operation over a wide temperature range must be insured.
5. Satisfactory operation of a given unit over a wide variation in system voltage must be assured.
6. In the case of the secondary network application, the device must not interfere with or be affected by high-voltage d-c cable testing.

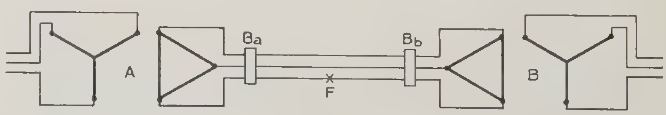


Fig. 1. A typical delta-connected line section

Line sections of this type usually are not protected for ground faults

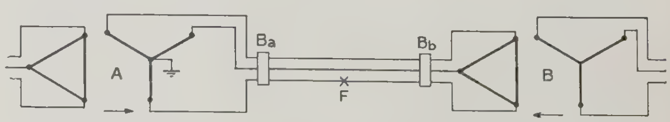


Fig. 2. A typical line section grounded at one end

This line section cannot be isolated by current relays. Circuit breaker B_a may be opened but a ground fault at F draws no appreciable current from B_b

Full text of a paper recommended for publication by the A.I.E.E. committee on protective devices. Manuscript submitted Feb. 23, 1934; released for publication Sept. 7, 1934. *Not published in pamphlet form.*

7. The equipment must be as reasonably inexpensive as possible without jeopardizing reliability.

Several schemes immediately suggest themselves as possible solutions to the above specifications. Wye connected potential transformers have been used occasionally for certain applications of this type. Potential transformers, however, are expensive, especially at higher voltages, and furthermore, they cannot be applied to cables which are tested with high voltage direct current.

A capacitor coupling device is also a possible solution to the problem. Here again, however, the installation is costly, and one which in many cases will be difficult to mount. Moreover, it was found in testing a capacitor coupling device that the range in system voltage which would give satisfactory relay operation was limited to a rather narrow band.

A third alternative, and the one which was finally adopted, consists of a resistance coupling device. Such a device must necessarily be of extremely high resistance in order to insure negligible losses. Moreover, it must have a nonlinear characteristic to permit selectivity over a wide range in system voltage.

A considerable amount of research led to the development of a new thyrite having extremely high resistivity and a highly nonlinear characteristic, both properties being essential and necessary to a highly sensitive resistance coupling unit. Coördinated with the thyrite development was the development of a new 3-electrode cold-cathode tube (shown in Fig. 11) having the necessary characteristics to control a relay circuit from the potentials impressed by the coupler unit. The coördinated design of the various elements of the device has resulted in a relay combination having a high degree of sensitivity, selectivity, and reliability.

The Coupler Unit

The simplicity and ruggedness of the coupler unit are evidenced in Fig. 3 which shows a design for 13,800-volt applications. The connections for the essential elements of the coupler together with its associated relay circuit as it would be applied to a typical secondary network transformer and protector are shown in Fig. 4. The several elements of the device may be identified as follows:

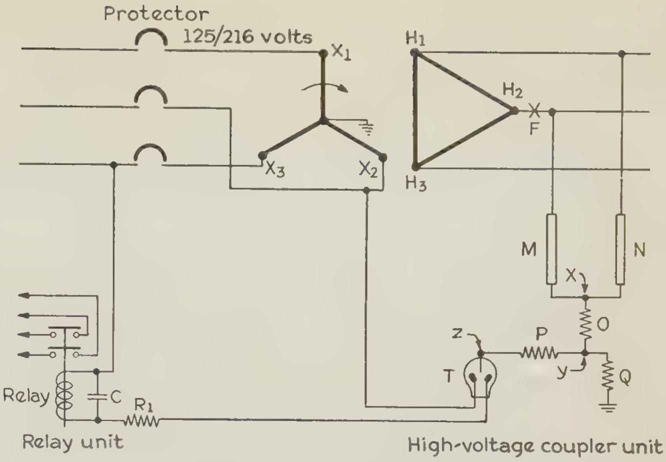


Fig. 4. Recommended connections for the high voltage coupler and relay units when applied to a secondary network transformer and protector

The elements of the coupler unit may be identified in Fig. 3 and the elements of the relay unit may be identified in Fig. 7

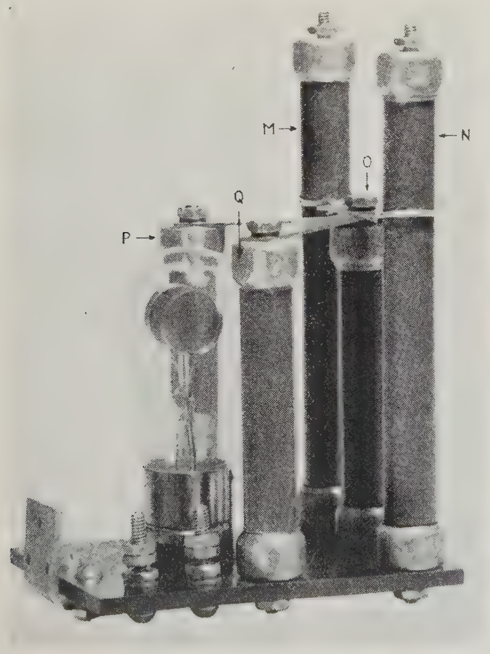


Fig. 3. The new high voltage coupler unit

This unit was designed for mounting inside a transformer tank under oil and for direct connection to the 13,800 - volt studs. Elements M and N are the porcelain bushings which house the thyrite resistors. Elements O, P, and Q are the porcelain bushings which house the linear resistors

Elements M and N are the thyrite resistors which connect directly to 2 of the high voltage conductors. These are the nonlinear resistors which normally have an extremely high resistance. The resistance of each may be defined by the voltampere relation:

$$e = Ci^{0.16}$$

where e is the impressed volts, i is the resulting current in amperes, and C is a constant having a value of from 50,000 to 500,000 ohms depending upon the particular application.

Elements O, P, and Q are linear resistors likewise having high resistances but relatively small as compared with the resistances of elements M and N.

The tube T is a small 3-element cold-cathode glow tube. The relay is a sensitive a-c relay.

Essentially the coupler unit is a potentiometer connected between line and ground, the potential at point Y being impressed through current limiting resistor P on the grid of the glow tube.

Under normal conditions, the resistances of M and N will be large compared with the resistances of O, P, or Q; and points x, y, and z will be, for all practical purposes, at ground potential. This means that leg voltage (i. e., 7,980 volts in this case) is normally impressed on both M and N. The normal current in both M and N will be approximately 1.9 μa (rms); in O approximately 1.9 μa; and in both P and Q approximately 0.9 μa. Thus, the normal loss in the device will be roughly 0.030 watts, which is negligible.

In the event of a ground fault at point F, the potential of point x will be drawn toward H_2 allowing approximately full phase voltage to appear across resistor N. But, whereas the potential across N has increased 1.73 times, owing to its nonlinear characteristic its current will have increased 25 to 30 times. Since this current flows through resistors O

and Q, the voltage drop across these elements will have increased likewise 25 to 30 times. Thus, in the event of a ground fault, the potential impressed at points y and z suddenly increases many times.

Normally, the tube passes no current between its electrodes since the impressed 220 volts is insufficient to maintain the arc drop. However, the several hundred volts impressed on the grid of the tube following a ground fault are sufficient to render the tube conducting. Thus, in the event of a ground fault the tube breaks down and passes the requisite current—some 20 ma—to pick up the relay.

The tube for this circuit is what is known as a positive tube. That is, the relay or secondary circuit of the tube is conducting only when a positive potential (i. e., a potential in phase with the voltage impressed upon the secondary circuit) of sufficient magnitude is impressed upon the grid of the tube. In Fig. 5 is shown the breakdown voltage of the tube as a function of grid potential, point A being the normal operating point for a fault at F. It is assumed in this curve that the control voltage and grid voltage are in phase.

Actually, the control and grid voltage are never in phase for any ground fault condition. For example, with a ground fault at F as shown in Fig. 4, the grid voltage $(H_1 - H_2)$ is 30 deg displaced from the secondary control voltage $(X_2 - X_3)$. Tests have shown that the circuit connection shown in Fig. 4 will always provide a sufficient component of grid voltage in phase with the control voltage to insure correct relay operation regardless of which phase is grounded.

It should be noted that the phase connections shown in Fig. 4 are not the only suitable ones. With the high voltage coupler connected to $(H_1 - H_2)$ the secondary circuit may be excited from either $(X_2 - X_3)$ as shown, or $(X_1 - X_2)$. Voltages separated by 30 deg should always be selected. Polarity and phase rotation appear to have slight effects, but, in general, these factors may be ignored in making connections.

Although the connections shown in Fig. 4 refer specifically to the secondary network application in which the control voltage of 220 volts alternating current is directly available, the same equipment may readily be applied to any other secondary voltage by using small step-down autotransformers; or, as an alternative, direct current may be used, if available, as an energy source in the relay circuit.

In the original tests on this device, 3 thyrite units, connected in wye to the 3-phase conductors, were used instead of 2 as shown. Later it was found that

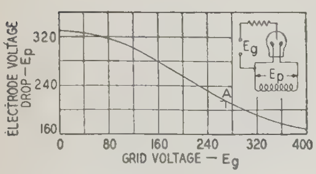
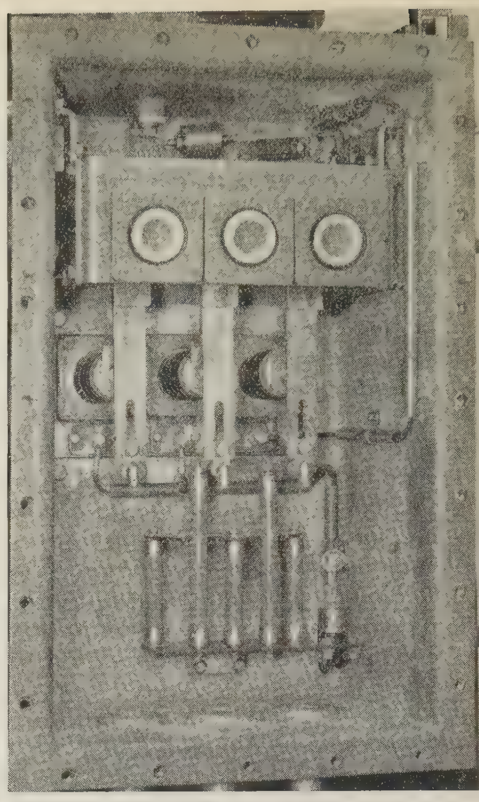


Fig. 5. Voltage breakdown characteristic of the new 3-electrode cold-cathode tube

This curve shows the in-phase 60-cycle grid voltage required to initiate current flow between the electrodes as a function of the applied electrode voltage. The grid voltage in this case was impressed through a 20-megohm resistor and the electrode current was limited by the impedance of the relay coil. Point A is the normal operating voltage for a fault on any one of the 3-phase conductors

Fig. 6. The high voltage coupler unit as it appears when mounted inside the grounding-switch compartment of a 3-phase network transformer



practically equivalent results might be obtained with only 2 units. The coupler using 2 thyrite units is preferable to one employing 3, since, (1) it is less expensive, (2) it is readily adaptable to transformer banks composed of 3 single-phase units, (i. e., the coupler may be mounted in a single-phase transformer tank without requiring cable connections to either of the other 2 units), and (3) it is subjected to a less severe duty during the d-c cable test.

The Relay Unit

The elements of the relay unit are seen in Fig. 4 to consist of a sensitive relay, a capacitor, and a current limiting resistor. A photograph of the unit is reproduced in Fig. 7.

As noted above, the relay is excited and picks up its contacts in the event of a feeder ground fault, owing to the valve action of the glow tube. The relay and tube constants are such that the current in the relay circuit is approximately 20 ma rms when excited as a result of a ground fault. The current in the relay circuit is peaked, and, although alternating, flows only for a portion of each half cycle (this is due to the nonlinear characteristic of the thyrite as reflected in the grid action of the tube). Capacitor C is placed across the relay coil in order that the intermittent current which flows shall not cause a chattering of the relay armature. Resistor R_1 serves to limit the current in the relay circuit.

The contacts of the relay may be circuit closing and may be used for direct tripping of a circuit breaker or the network protector in the event of a feeder ground fault. The contacts may also be circuit opening and used to open the restraint circuit of a master relay so as to render it sensitive and capable of operating in the event of a feeder ground

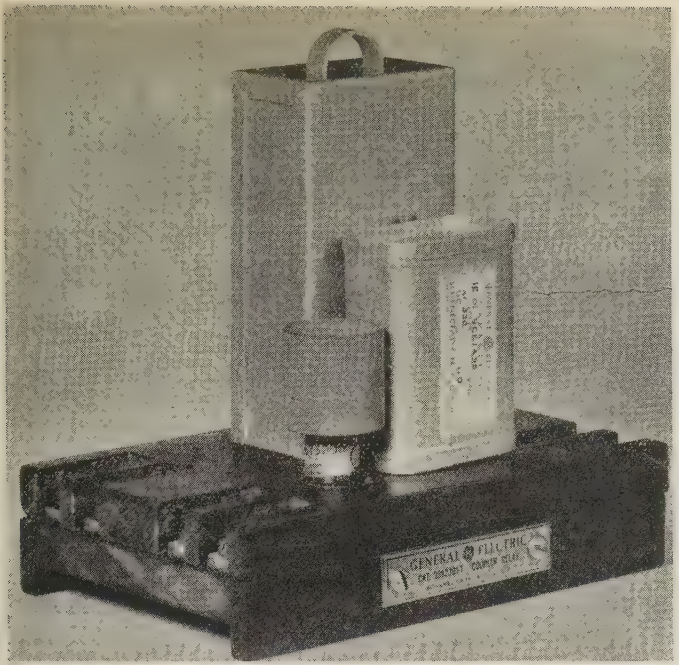


Fig. 7. A view showing the elements of the relay unit

fault. In this latter scheme the relay serves indirectly in providing ground fault protection.

Permissible Range in System Voltage

As has been pointed out, a particularly attractive feature of the coupler unit is the wide variation in system voltage over which it will perform successfully. The circuit of Fig. 4 will give successful relay operation for system voltages varying approximately from 80 per cent of normal to 118 per cent of normal.

These limits are based upon the condition that both the low voltage and high voltage terminals of the transformer are subjected to the same percentage of overvoltage or undervoltage. Operating conditions differ from this premise somewhat but in such a manner as to decrease the lower limit and increase the upper limit as specified above.

The upper voltage limit is that point to which the system voltage must be raised to cause the tube to become conducting even though a ground fault does not exist.

The lower voltage limit is that point to which the system voltage must be lowered to cause failure of the relay to pick up in the event of a ground fault. Although the tube will function properly for system voltages as low as 70 per cent, the relay itself begins to chatter at about 78 per cent of normal voltage and does not make a definite pick up.

It should be borne in mind that the lower voltage limit depends upon which phase is grounded. The limits specified above apply to the worst phase (i. e., the phase having the highest value of lower voltage limit).

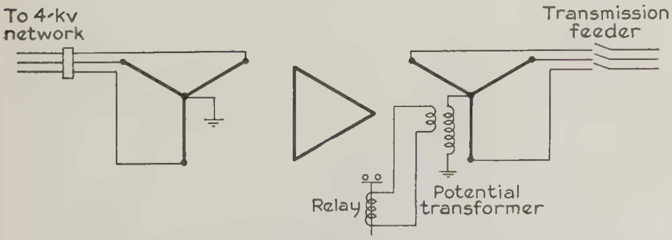


Fig. 8. A conventional method of obtaining ground fault protection on an ungrounded wye-connected feeder

High Voltage Cable Test

As has been stated, it is common practice to test feeder cables, particularly network feeders, periodically at high voltage direct current. A common test for 13.8-kv cables is an impressed 35-kv direct current for 5 min from the 3 conductors to ground. Since the high voltage coupler unit is permanently connected to the feeder—and there may be as many as 60 such units per feeder—it is essential that:

1. Each coupler unit be able to withstand the high potential without overheating or suffering a change in characteristic; and that
2. The total current load imposed by all of the coupler units on a feeder shall not exceed the permissible loading of the vacuum tube test set.

With an impressed voltage of 35-kv direct current, the current flowing through the coupler unit to ground will vary somewhat with the type of test set used, with the temperature of the transformer oil (the resistor units and their porcelains assume the temperature of the transformer oil under normal conditions), etc. However, in general, the ground current through the unit will not exceed 400 μa (rms) with an impressed 35-kv direct current. In Fig. 12 is shown the voltampere characteristics of the various elements of the coupler unit. An over-all characteristic of the resistor elements as they are connected for the 35-kv d-c test is also shown (i. e., the 2 thyrite resistors paralleled and in series with resistor *O*, and with resistors *P* and *Q* paralleled as shown in the insert). Note that, although resistor *P* is grounded only through the tube, the resistance of the tube is small and may be ignored. This over-all characteristic is a theoretical curve and shows that for an impressed voltage of 35-kv direct current the ground current will be about 450 μa. Actually, tests have shown that this value is never reached.

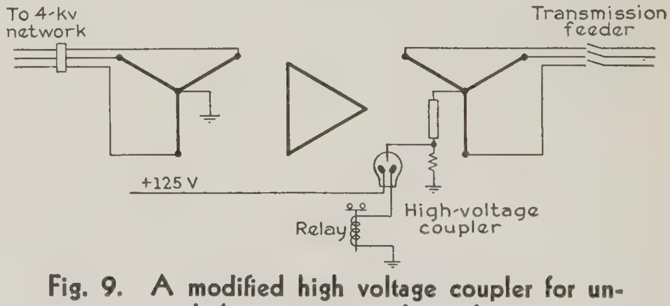


Fig. 9. A modified high voltage coupler for ungrounded wye-connected transformers

This arrangement is a modification of the high voltage coupler and relay assembly for ground fault protection on wye-connected transformers. It is preferred to the scheme shown in Fig. 8 owing to its reliability and low cost

As has already been pointed out, perhaps the most important application of the new ground fault protective scheme is on secondary network feeders. The value of the scheme in this particular case is augmented by its function in normal network operation apart from its function of ground fault protection. A distinct improvement in network operating efficiency and reliability has been obtained by applying the new device.

Consider for a moment the particular network operating characteristics and problems which are pertinent to the present application:

The secondary network consists of a number of primary feeders (13.2 or 13.8 kv in most cases), up to 50 or 60 protector and transformer units tapped to each feeder, and the 125/216-volt secondary grid. The network transformers usually have delta-connected primaries and wye connected secondaries. The conventional network relay equipment consists of a master network relay and a phasing relay which are arranged to function as follows:

1. A reverse power flow in the transformer of the order of magnetizing current will be sufficient to trip the protector. This so-called sensitive tripping is desirable since it allows the feeder to be taken out of service by the simple operation of opening the station circuit breaker, and furthermore, it provides feeder protection in the event of ground faults as well as the current-bearing phase faults.

2. A feeder which is out of service will automatically be restored to service if its voltage is of proper magnitude and is leading the voltage of the network grid.

Sensitive tripping has been found objectionable in certain cases since it results in excessive and unnecessary protector operations owing to feed-backs from regenerating elevator motors or to circulating currents arising from slight differences in feeder voltages.

Therefore, in view of the above general requirements and of the objections to sensitive tripping in some cases, the specific problem is to provide a supplementary relay device which will (1) permit the network feeder to be removed from service automatically by some simple operation at the station, (2) provide nonsensitive protector operation under normal conditions, and (3) provide sensitive protector operation in the event of a ground fault. It should further be stipulated that any scheme adopted must not interfere with or be affected by the high-voltage d-c cable test to which the feeder and all connected equipment is periodically subjected.

If a network protector be made sensitive to ground faults, it is evident that a plausible and simple method of taking the feeder out of service at the station is to open the station circuit breaker and ground one conductor. Thus, requirements 1 and 3 noted above may be accomplished by exactly the same device and in the same manner. At least one solution to the problem, then, consists of a ground sensitive relay which renders a normally nonsensitive power-directional relay sensitive in the event of a ground fault.

The high voltage coupler and relay unit described above offer an ideal solution to these network operating problems. The coupler is especially attractive for this application since it is not only highly reliable as a unit but it in no way impairs the reliability of the feeder itself.

The particular advantages of the new relay combination for secondary network applications may be summarized as follows:

1. Ground fault protection over a wide range in system voltage is assured. This is important since the voltage of a network feeder may vary considerably under the several normal and emergency operating conditions.

2. Even though as many as 100 couplers are connected to a single feeder, they are not appreciably affected by, nor do they affect, the periodic high-voltage d-c cable test.

3. Improved reliability of the network is definitely assured since the ground relay permits nonsensitive tripping of the protector, thereby eliminating excessive operations.

4. Complete control of the feeder at the station is possible by the

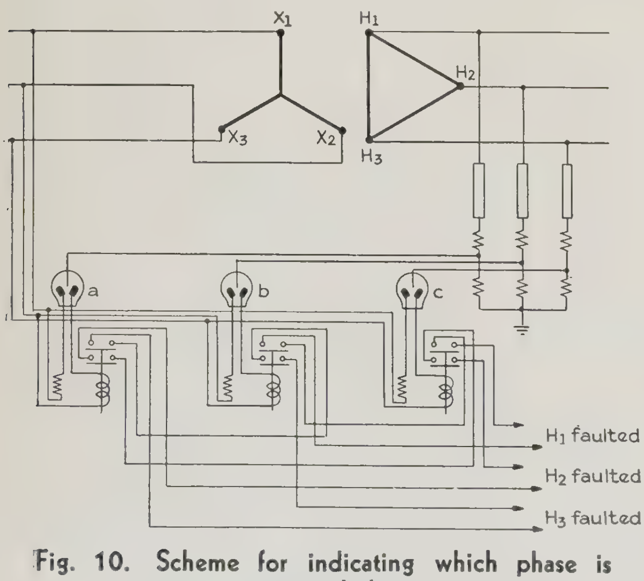


Fig. 10. Scheme for indicating which phase is grounded

This arrangement is a modification of the high voltage coupler and relay assembly shown in Fig. 4, and is designed to give not only ground fault protection but also an indication of the particular phase which is grounded

Fig. 11. The new cold cathode tube

This new 3-electrode tube was designed especially for the new ground protection scheme. It functions to control the relay circuit as dictated by the high voltage coupler

simple expedient of opening the station circuit breaker and grounding one conductor.

5. The equipment will operate successfully over an unusually wide temperature range and a wide variation in system voltage.

6. The coupler unit may be mounted directly in the transformer tank or ground-switch compartment (under oil) of either a single-phase or a 3-phase transformer without the necessity for any external high-voltage cable connections. The relay unit will usually be mounted in the protector; and if the protector is attached to the transformer, as is frequently the case, the installation becomes a very simple one. (See Fig. 6 for a typical installation of the coupler unit.)

Applications to the Primary Network

The application of the new relay equipment to primary networks is of particular importance because it permits the use of a delta-wye transformer instead of the more costly wye-wye or wye-zigzag with delta tertiaries. In some of the early primary network installations, the transformers were wye-wye, delta tertiary with solidly grounded neutrals. Ground fault protection was insured with this arrangement since all ground faults drew sufficient current to operate the phase current relays. The wye-wye transformer is not acceptable in many cases, however, owing to the desirability of tying the network in with an existing delta-wye radial substation.

In the past, where such tie-ins have been expedient, wye-zigzag transformers have been adopted.

It has not always been desirable to ground the neutral of the high voltage windings, in which cases a neutral potential transformer has been used for ground fault protection as shown in Fig. 8. This arrangement is costly, especially at the higher voltages.

All of these difficulties and expensive expedients are removed by application of the new ground relay. The simple delta-wye transformer may be used with ample ground fault protection assured.

If for any reason a wye-wye transformer should be preferred, the new scheme may be applied in a simplified form as shown in Fig. 9. This arrangement is less expensive and probably more reliable than the potential transformer arrangement shown in Fig. 8.

The high voltage coupler and relay assembly is directly applicable for ground fault protection on primary network feeders in a manner similar to the secondary network application described above.

However, whereas in the secondary network application the relay functioned indirectly to isolate a grounded feeder by removing the restraint from the master relay, in the primary network application the relay functions directly to trip the circuit breaker; or, if desirable, it may operate directly to trip the circuit breaker through an auxiliary time-delay relay. Unlike the secondary network feeder the primary network feeder serves relatively few network units and there is no need for control of the feeder at the station and, therefore, no need for highly sensitive power-directional relays. In the primary network, therefore, the ground relay scheme serves only to isolate ground faults.

There is another fundamental difference in the application of the ground relay to the 2 types of network. In the secondary network, excitation for the relay circuit is obtained from the 216/115-volt grid as shown in Fig. 4. In the primary network, the network potential is 4,000/2,300 volts and excitation for the relay circuit must be obtained from the auxiliary power transformers which are standard equipment with each network unit.

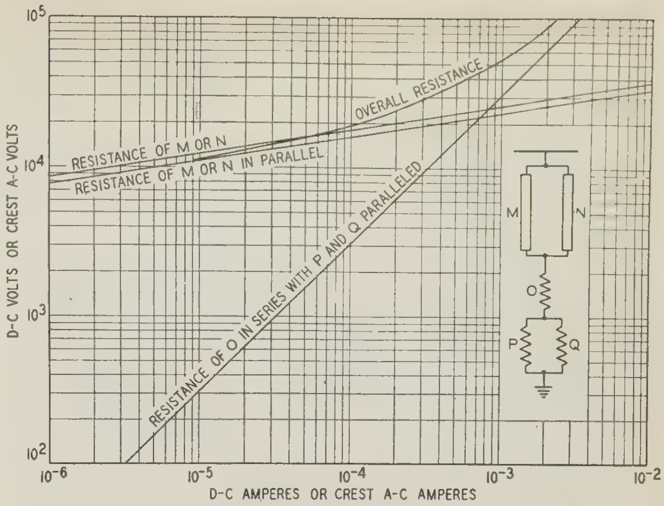


Fig. 12. Resistance characteristics of the high voltage coupler unit

These curves show the resistance characteristics of the 5 elements of the high voltage coupler unit designed for 13,800 volts. The over-all resistance curve is that resistance which limits the current in the unit when the cable to which it is connected is tested at 35-kv direct current to ground

Other Applications

The foregoing applications have been concerned with the primary and secondary networks. There are obviously many other applications on ungrounded line sections such as sections in loop circuits and tie lines.

It should be borne in mind that, by simply changing the resistor constants and insulation clearances, the coupler unit may be designed for any line voltage. Thus, for even the highest voltage, the new relay provides a relatively inexpensive and highly reliable device for isolating or detecting ground faults.

In some cases it will not be desirable to trip a circuit breaker to isolate a ground fault but only desirable to give an indication of the presence of the fault. For detecting ground faults, the new equipment has an advantage over conventional ground detectors in that it permits relaying the signal to a point remote from the grounded bus or line.

In addition to detecting a ground fault on a line, it may be desirable to detect also the particular phase which is grounded. A modification of the fundamental circuit to accomplish this result is shown in Fig. 10. Note that 3 relays and 3 tubes are required and that an additional high voltage resistor unit is required. If phase H_1 is faulted, relays *b* and *c* operate; if phase H_2 is faulted, relays *a* and *c* operate, etc.

Vibration Analysis—
Transmission Line Conductors

A method of measuring the stress distribution in transmission line conductors caused by vibrations under actual service conditions, and the effect thereon of various attachments, is outlined in this paper. Measurements have been made of the attenuation of traveling waves in conductors, reflection factors of supports, ratio of the bending at a clamp to that in mid span, effect of vertical rigidity of the support, impact effect of traveling waves, stress division effected by a rocking clamp, and other items. Some records of aeolian vibrations are included which indicate a periodic recurrence of similar groups of waves at time intervals equal to the double-span time-interval of a traveling wave.

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CAREFUL reading of much of the best literature on the subject of vibrations of transmission lines and their harmful effects, supplemented by field records and observations, indicated that while the over-all effects reported with respect to various devices for suppressing vibrations might be quite satisfactory there was still much to be desired in the rigor of the methods of analyses and a scarcity of the types of measuring or recording devices which would furnish the basis from which such analysis could be made.

The immediate and most pressing need called for decisions based upon the conditions existing in hundreds of miles of lines already installed and operating. Hence equipment by which a line could be tested with not more than a few hours' interruption seemed to be the first objective. The specific problem thus reduced to: First, the development of a satisfactory method of testing lines and attachments in place, as to vibration characteristics, with the measuring equipment adapted therefor; and second, testing with the view to determining quantitatively the relative merits of various devices that have been tried or might be proposed for the purpose of mitigating harmful effects of vibrations.

This paper deals with the method of testing and the equipment used. Some data of considerable value are also included, the purpose at this time being to demonstrate the validity of the method and to point out some of the most important principles involved in the protection of lines already built.

The facilities subject to requsition by the investigating staff included not only the extensive electrical and mechanical equipment of the laboratories of the Hydro-Electric Power Commission of Ontario, Canada, but a line of towers was available where at 2 convenient locations any type of line conductor and assembly could be mounted and tested as desired. One of these locations was quite favorable to the development of the so-called "natural vibrations" and such vibrations were observed and recorded on several occasions.

First efforts were directed to establishing standing waves on conductors in such a manner that the characteristics of conductors and devices could be observed and evaluated by test. Great difficulty was experienced in obtaining any satisfactory method of controlling such waves by any scheme suitable for field testing. Moreover, it was observed that in natural vibration the standing wave was a rather transient phenomenon, node points were continually changing and wave lengths changed within short periods and considerable agitation of the conductor was apparent prior to the observation of any standing waves.

Without commenting adversely at all on the very valuable work that has been done theoretically and practically on the formation of eddies, it did seem quite improbable that eddy currents of air could be so highly selective in space as to determine where node points should or should not occur. Observation indicated and subsequent tests tended to prove that any major disturbance of the conductor in space resulted in a traveling wave in each direction from that point, reflections occurred at points of support or where appreciable masses of material were rigidly attached, and in a few seconds these and subsequent reflections passing in opposite directions gave the appearance temporarily of standing waves.

Mathematically it can be shown that a standing wave is the result of 2 traveling waves equal in magnitude but of opposite direction of motion, hence to set up any large number of standing waves in a line conductor it would be necessary to have a succession of waves with practically undiminished reflections. This difficulty doubtless accounts for the constant shifting of node points and generally unstable conditions noted previously. It thus appears that since a standing wave is only one special case involving 2 traveling waves, any solution therefor could only be accepted as a special and not as a general solution without further consideration.

Such observations led to the conclusion that for the present purpose, testing with a single traveling wave should provide the means leading to a more thorough study of the stresses involved. Given suitable recording devices, a traveling wave could be applied to a conductor and its attenuation would

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be a definite measure of the energy loss in such conductor at that tension, amplitude, and wave length. The behavior of various suppressors or absorbers could also be determined by similar means in exact quantitative terms.

Methods of measuring energy loss from the decrement of electric or mechanical oscillating circuits are generally accepted. A similar analysis made from the attenuation of a mechanical wave as it travels from point to point on a conductor should be equally valid providing there be no appreciable distortion of wave shape.

It has been suggested that because the view that all vibrations on transmission lines originate as traveling waves is quite radical, an extra effort should be made to establish the validity of such an hypothesis. It may be accepted more readily if brief reference be made to some of the better known cases of vibration of strings as they behave in stringed instruments. It might be stated here that on actual tests on the lines quite high reflection factors have been measured; from 92 to 98 per cent is reflected from supports which are, according to present practice, considered to be among the best types. Hence the condition is more nearly comparable with that of the stringed instrument than might at first appear to be the case.

A piano wire is struck, a guitar, banjo, or mandolin string is plucked and obviously the displacement is initiated in the same manner as is adopted to apply a traveling wave on the line. The order and magnitude of the harmonics of the initial wave (transient) depend upon the force of the blow, the hardness of the materials at the point of impact, and the distance from one support where the string is struck or plucked. The mechanical oscillation (sustained) is determined by the mechanical characteristics of the system and some acoustic modification by the form of the sound box. In the present tests we are not interested in a sound box but all the other components enumerated have a part in dictating where and how the wave should be applied so that the record might be suitable for computation.

Fig. 1. Damped oscillation record of a solid steel rod taken by a carbon pack curvature recorder

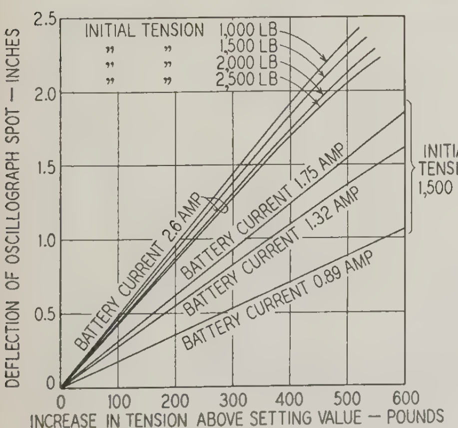

Fig. 2. Calibration curves of a carbon pack tension recorder on 3/8-in. diameter ground cable

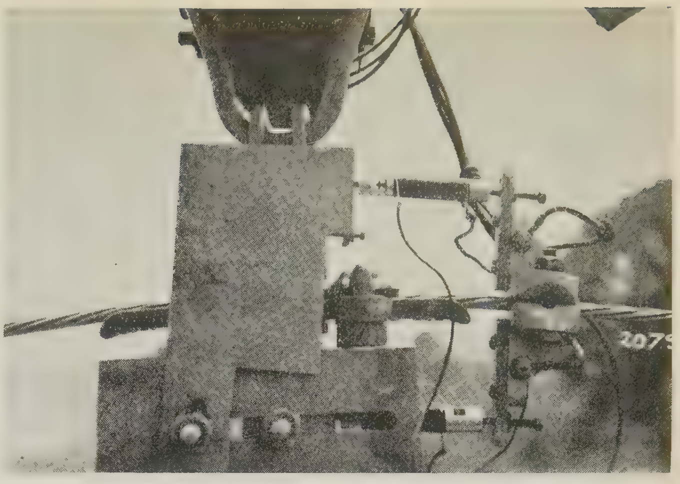

Fig. 3. Carbon pack curvature recorder

The same analysis applies to stringed instruments which are excited by a bow, with the additional complication that the string is subjected to a series of minute impacts resulting from a high ratio of static to moving friction between the bow and string. Thus a very wide range of tone, color, pitch, and volume can be obtained by varying the magnitude and character of the component noted above as transient relative to the sustained component. Practically this is done by varying the pressure and velocity of the bow, the contact area, and the distance from the bridge. The conclusion then seems justified that in this more complex case the result is derived from the summation of a series of traveling waves and their reflections.

Test Apparatus Which May Be Used

After a critical review of such methods as had been used elsewhere it was decided that to obtain satisfactory records in permanent form at locations remote from the occurrence of any event at the frequencies used it would be necessary to use an oscillograph in combination with suitable devices for supplying the current. A portable 2-element oscillograph which operated from a 6-volt storage battery was available and has been used throughout the tests to date.

Some practical work had been done in the laboratory on carbon pack resistors and their application to remote measurements of stress and displacements but such development work is slow, uncertain, and expensive. The information obtained from the U.S. Bureau of Standards Technologic Paper No. 247 was of considerable value, especially in the preparation of the carbon disks for the resistance units. These units have been very satisfactory, as is shown, for example, by the damped oscillation record (Fig. 1) of a solid steel rod (taken by a curvature recorder) and that of a tension recorder (Fig. 2) calibrated up to 2,500 lb in 5 stages of 500 lb each.

Analysis of the transient stress to which a conductor is subjected by vibrations indicates a component or unbalancing due to bending and an average longitudinal component. Hence if direct measurement could be made of these quantities inde-

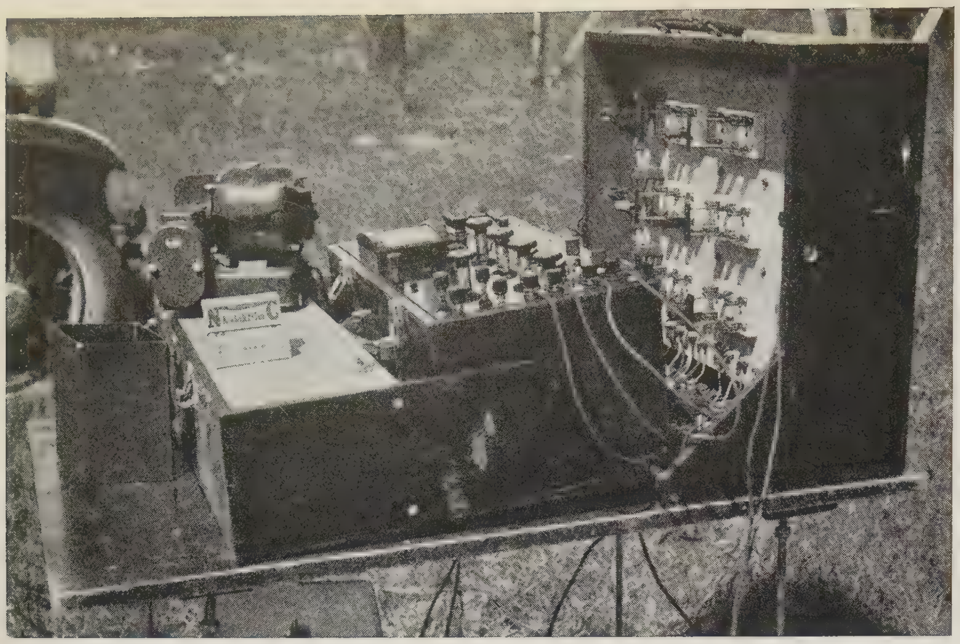

Fig. 4. Assembly of the equipment used with the carbon pack curvature recorder for use in the field

blows, mechanical devices, and by hand, and thus far the most satisfactory, in fact the only usable records, have been those obtained when the wave was applied by hand. Some skill and experience is necessary to develop the proper "sleight of hand" to duplicate results; this phase of the problem at present is something of an art.

Keeping the records of various events separated so that valid measurements might be made requires certain precautions in placing recorders and choosing the point of application of the wave. When a wave is initiated by vertical displacement of the conductor, at, say, the center of the span, 2 waves are started, one in each direction, of identical shape. The steepness of the wave front depends upon the relative velocity of the vertical displacement and the longitudinal velocity of this lateral wave. The amplitude depends on how far it is displaced, and the shape of the tail on the rate of restoration to its initial position. It is advisable to force this return in order that the length of the wave be limited, otherwise the tail would be a long taper, similar to that of a lightning stroke, and interfere with the recording of reflections in their correct magnitude.

A "lattice" diagram has been so useful in visualizing what occurs and such an aid in identifying the various components that it seems advisable to discuss briefly its construction at this point and note some of the important features of the problem before undertaking the solution of any given set of test results.

One axis of a plane rectangular coördinate system is assumed to represent distances along the length of the conductor and all items of apparatus, *e. g.*, tower supports, recorders, suppression devices, etc., have their positions indicated to scale. The other axis indicates time as measured from the instant of application of the wave. The progress of the main waves and the various reflected components are then represented by lines of uniform slope depending upon the velocity of the waves and the scales represented by the 2 coördinates. A typical diagram has been drawn for a 1,400-ft span, curvature and amplitude recorders at 500 ft from the easterly tower and wave applied at the center of the span. (Fig. 5.) Initially the easterly and westerly traveling waves, denoted by E and W, are on the bottom of the conductor but reflections are thrown back on the top of the conductor, i. e., components of $-E$ travel westward while those of $-W$ travel eastward. This reaction corresponds to the reflection of a voltage wave at the end of a line which is grounded. The transmission coefficient of the recorder is noted as T, therefore its reflection factor is $(1 - T)$. The reflec-

pendently of all other influences they should give a direct measurement of the actual duty imposed on the conductor.

Two arrangements are therefore used. The curvature recorder (see Fig. 3) is mounted with its carbons in the plane in which the wave is applied, and in the present form weighs 11 oz. The tension recorder is mounted with its carbons at right angles to the conductor and to the plane of the wave travel. In each case the opposing carbons are connected as adjacent arms in a Wheatstone bridge circuit, the oscillograph being the detector and the common lead to the carbons from the supply circuit. Suitable rheostats are used for changing the current supplied to the network and thereby the sensitivity of the recorders. The equipment has been assembled in a carrying case in a manner very convenient for use in the field. (See Fig. 4.) This is the first time we have heard of such a curvature recorder having been used and its merits will be discussed more fully in connection with the interpretation of some records.

One other special device for use with the oscillograph should be mentioned, *viz.*, a slide wire resistance placed vertically against the conductor and giving a measure of the amplitude of the wave at that point at any instant. This is useful in demonstrating the relation that exists between the actual wave and the curvature recorder but is less useful than the latter because the actual elevation of the conductor at any instant is unimportant compared with the manner of its progress to that point.

Location and Method of Applying Traveling Waves

It seemed advisable to determine and use for test such wave fronts, etc., as might most nearly duplicate those occurring through the action of wind. Various schemes were tried, sharp hammer

tion factor of the tower support is indicated as R. Use of these symbols as coefficients permits the identification of the various transmitted components of the main waves and the various reflections therefrom. For simplification the coefficient indicating attenuation due to distance traveled is not written in the diagram but must always be considered in evaluating results.

Inspection of such a diagram identifies clearly the various waves as they pass the point C (location of the recorders) in either direction and also aids in the interpretation of unusual results obtained when waves of opposite direction of travel interfere at this point.

It has been implied that the velocities of these waves are independent of the actual wave lengths and that there is no interference between waves traveling in the same direction. The formula for this velocity is $v = \sqrt{T/m}$ where T is tension and m is mass per foot length. This does not involve wave length. Practically, it is found that the time of travel of a wave from one support to the next and back is the same regardless of whether the wave be applied by a hammer blow or by hand. Also it is deduced from records that unless a wave is subjected to some distorting interference, *e. g.*, reflected components, etc., it will pass through several reflections back and forth in a span without appreciable change in wave shape, the change being one of amplitude only. The latter fact has rather greater significance than might at first be apparent, for the following reason:

The wave is initiated as a lateral displacement of material, traveling lengthwise of the conductor in space at an approximately constant velocity. The record interprets this as a displacement with respect to time. Hence, the record, properly interpreted, indicates the form of the wave at any instant while traveling freely in space. It is usually distorted, that is, not sinusoidal, but might be represented between certain limits, by a Fourier series. The higher terms in such a series would indicate components of shorter wave length and if the velocity of travel of such components were different from that of the fundamental some appreciable change in wave shape should be evident. Any change that has been detected so far has been traceable to some other agency and it appears to be definitely established that for the conductors, spans, and other conditions involved, the transmission of the traveling wave is distortionless.

During periods of testing it is frequently difficult to obtain a quiet condition in the conductor due to oscillations continuing from a former test or to natural vibrations. At such times it is necessary to use waves for test which are substantially greater in value than the interference waves just as in communication it is necessary to maintain the energy level of communication well above that of the background of interference. Such phenomena are fairly common and require very little comment other than to point out that very erratic results might be obtained if due attention be not paid to this feature.

Progress to this point justifies a restatement of the problem, *viz.*—given the means of faithfully recording the components of the stresses it is desired to investigate, and a means of initiating a disturbance approaching the character and magnitude of those considered most hazardous it should be possible to analyze the distribution of loss and learn the direction in which improvement in equipment might be expected. The quantities it is desirable to measure include the attenuation due to loss in the conductor itself, reflection factors at supports or other attached masses, and the distribution or concentration of stress at such reflection points.

No general rule can be given but each test must be planned in accordance with the information required. A variety of examples will be given to indicate the great possibilities of this method of analyzing the transient components of stresses due to vibrations of line conductors.

Example 1—Relation of Curvature to the Amplitude of a Wave

Initially it was planned to measure the rate of loss of energy by noting the decrease in amplitude of a wave after it would have passed through one or more types of experience. Obviously, there would be practical difficulties in mounting an amplitude recorder 50 or 75 ft in the air at 200 ft distance from a tower, but it is possible to do this with the curvature recorder. It is necessary then to determine if the values, as indicated by the latter, could be used as a measure of the rate of energy absorption or dissipation taking place in the system.

The radius of curvature is usually expressed by a rather complex differential equation of the second order. The physical conditions of this test, however, permit the calculations to be based upon values at instants when the first derivative becomes zero and the curvature itself becomes equal to the second derivative which is directly proportional to the amplitude, *e. g.*, if $Y = A \sin X$ then $d^2y/dx^2 = -A \sin X$.

Reference to Fig. 5 will aid in visualizing the relation between the curvature and amplitude records

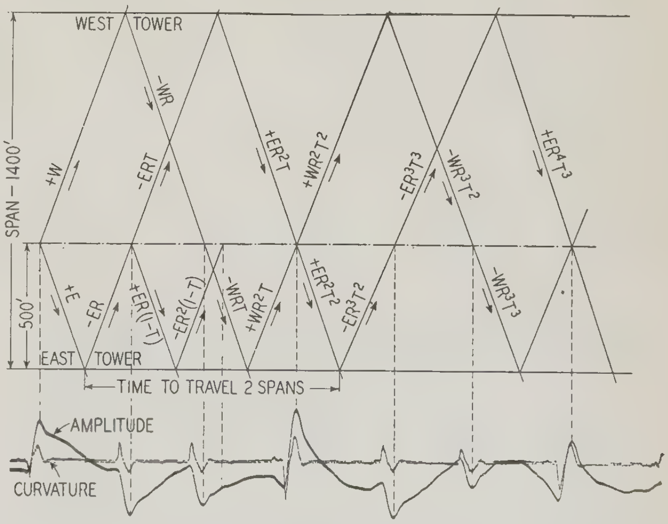

Fig. 5. A typical "lattice" diagram drawn for a 1,400-ft span

under conditions nearly ideal. It may be observed on close inspection that a long tail on a preceding wave may affect both amplitude and curvature records. The former would be also affected seriously by a slow sway of the conductor. The latter is practically independent of any swing of the conductor, recording only the changes in curvature from instant to instant. For the traveling wave this is usually consistent. It will be evident that considerable care is necessary to identify the registrations which are comparable for analysis. Though difficult this has not been found to be impossible if certain precautions have been taken in planning and carrying out the test.

Example 2—Calculation of Attenuation and Reflection Factors

The tests resulting in this series were devised to check line attenuation and reflection factors by sufficient readings to set up the simultaneous equations which would evaluate these quantities. The general principle and method of solution is as follows:

The record, Fig. 6, was obtained by applying an impulse at P_2, the wave W_1 traveled through recorder T_2 to S_1 and was there reflected. Wave W_2 first traveled west and was reflected at S_2.

Wave W_1 first gave record A, then after reflection at S_1 it gave C then traveled to S_2, was reflected, and on its return gave A' and C' etc.

Wave W_2 first traveled to S_2 was reflected and gave record F when passing through T_2, was reflected at S_1 giving record H. This wave continued to travel back and forth in the span until it was dissipated.

Recorder T_1 shows practically no component whatever transmitted past the support so that in this case the total loss occurs within the conductor of the span and at the 2 supports.

The distance S_1T_2 should be known or it could be estimated from the record by assuming uniform film speed and uniform wave velocity, neither of which were strictly true. The length of film A to A' is proportional to twice the length of span, and from A to C to twice distance S_1T_2.

The attenuation ratios A'/A, C'/C, F'/F, H'/H are the result of the waves traveling 2 span lengths and being subjected to 2 reflections.

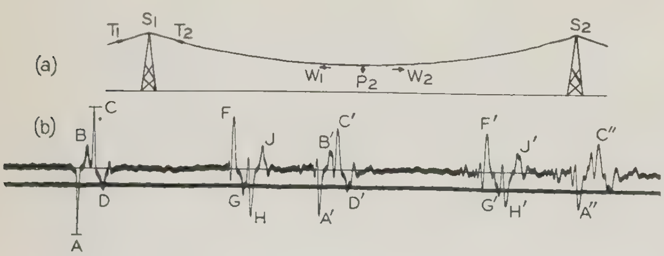

Fig. 6. Vibration record obtained with recorders at T_2

1,400-ft span of 795,000-cir mil aluminum cable steel reënforced conductors
Recorders 87.5 ft from east support
West span plucked by hand, 500 ft from support

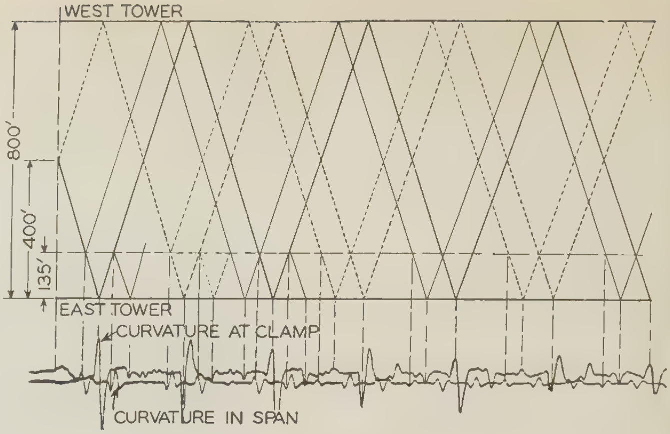

Fig. 7. Record indicating ratio of curvature at clamp to curvature in mid span

Record taken on a 5/16-in. steel-conductor 1,800-ft span at approximately 650-lb tension

The attenuation ratios C/A, H/F, C'/A', H'/F' are due to the travel of the wave along 175 ft of conductor and one reflection.

Using R to indicate the reflection factor of the support and with similar construction assuming that these factors for each end are equal, also J to indicate the attenuation due to conductor loss in the length of conductor indicated by the subscript, there are obtained by scaling the records:

$$RJ_{175} = 0.93$$
$$R^2J_{2,800} = 0.70$$

From which are obtained

$$R = 0.945$$

and

$$J_{1,000} = 0.92$$

These figures indicate that for this particular conductor at the tension given there is a reduction in amplitude of the wave of 8 per cent in 1,000 ft of travel, and it may be assumed to be uniformly distributed. There is also indicated an energy loss at the clamp sufficient to reduce the amplitude of the reflected component by 5.5 per cent. The stress distribution at the support, however, is extremely variable and requires a special series of tests for its determination.

Example 3—Ratio of Curvature at Clamp to Curvature in Mid Span

This phase of the general problem has been studied with the aid of the curvature recorders on several types of conductors and with various types of clamps and other modifications in the supports. The record shown in Fig. 7 was taken on a $^5/_{16}$-in. steel-conductor 800-ft span at a tension of approximately 650 lb. The corresponding lattice diagram serves to identify the various components as they appear at 2 locations, at the support and at a distance of 135 ft. The relative sensitivities of the 2 measuring elements is such that this recorder indicates a curvature at the clamp 20 times as sharp as that occurring at 135 ft from the clamp. A corresponding record after the installation of a

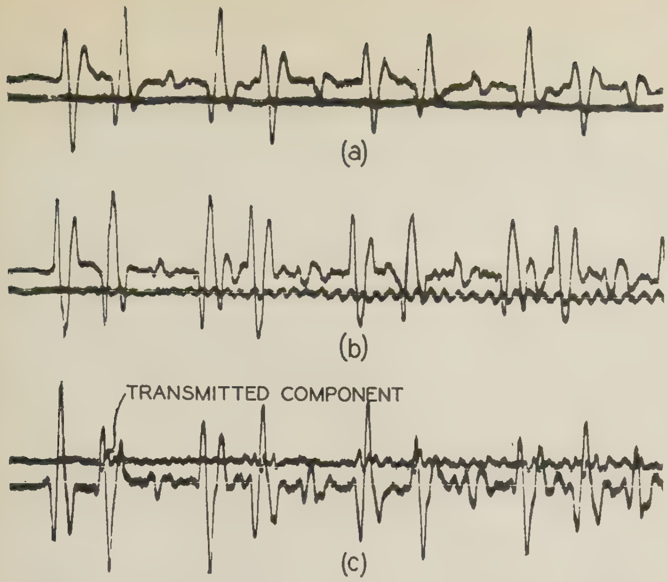

Fig. 8. Recording indicating effect of vertical rigidity of support

festoon gives a reduction of this ratio to 11, or about 55 per cent of its former value. The attenuation factor for 2 reflections and 2 span lengths of wave travel is not so pronounced, dropping from 0.871 to 0.61.

These ratios should not be taken as a criterion of the best results that can be obtained by festoons, but are submitted in order that a perspective may be obtained as to the duty imposed on the conductor at this point.

Example 4—Effect of Vertical Rigidity of Support

Since a high reflection factor is one of the elements tending to increase the stress due to bending at a support, some consideration was given to the essential features involved in developing a transmission factor for wave travel through the clamp. Oscillogram Fig. 8*a* taken with conductor arrangements similar to those in Fig. 6 and rigid suspension shows that the transmitted wave is negligible.

A spring suspension with limited travel was used to support the clamp, and oscillogram Fig. 8*b* was obtained. An increase in the oscillations in the adjacent span is apparent and this can be traced to the transmitted component through the clamp. The relation, however is much more definitely indicated by oscillogram Fig. 8*c* taken under similar conditions but with the clamp having 3 times as much freedom in a vertical line as in the previous case. During this test the wave was applied in the east span and the transmitted wave would appear on the record for the west at the same time as the reflected wave would appear on the record for the east span. In this case it is of appreciable magnitude and can be identified in wave shape with the original wave.

Other investigators have sought to discover some relation between the vibrations on opposite sides of a support but as far as we are aware they have been shown to be mutually independent. This experiment suggests the reason, namely, that unless there is elasticity of the support the synchronizing force between oscillations in adjacent spans is negligible.

Example 5—Longitudinal Component of Traveling Wave; Impact

The longitudinal components of the 2 traveling waves which result in a standing wave may be assumed to neutralize each other and the net effect of such components is to tend to reduce the effective length of the conductor. This action has the general effect of slightly reducing the sag of the span.

The unbalanced traveling components, however, are likely to produce an impact effect at supports or other masses. In fact, what appear to have been oscillations of a longitudinal wave between supports have been set up by the impact of a traveling wave of steep front. Such oscillations have been highly damped and are not likely to be of much practical importance.

In Fig. 9 is a record taken on a $^3/_8$-in. steel-conductor 1,400-ft span at 1,420-lb tension. The curvature recorder was mounted 75 ft from the tower and gave the upper record. A tension recorder at the support gave the variation in the total tension and the calibration in this case indicates a variation of plus and minus 75 lb. The magnitude of the wave was such as to approach the conditions involved in dancing or galloping conductors so might be assumed to represent the result of rather severe conditions.

Example 6—Flexibility of Conductor; Variation of Attenuation With Tension

A special type of hard-drawn copper conductor of section equivalent to about No. 4/0 was strung on a line of towers using 6 10-in. suspension units per support, and attenuation tests were made by checking the curvature record at one support during 10 spans of wave travel.

With an initial tension of 2,000 lb an attenuation coefficient of 0.94 per double span was estimated. This value includes both reflection factors of the supports and reduction due to loss in the conductor itself. Similar readings at 1,770-lb tension resulted in a coefficient of 0.895.

Greater per cent loss in amplitude at the lower tension is indicated but the figures do not give the complete story of the test. In the latter case a series of waves were slowly built up, following the main

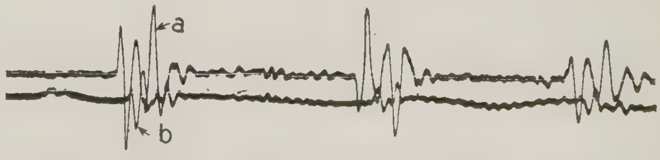

Fig. 9. Record indicating impact effect at support

a. Curvature record 75 ft from tower
b. Tension record at tower
1,400-ft span of 3/8-in. steel conductor at 1,420-lb tension

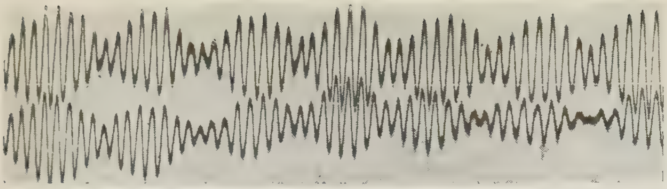

Fig. 10. Records with curvature recorders at opposite end of a flexible suspension clamp

wave, which doubtless were derived from the main wave and represent part of the energy loss from the main wave. Except for change in tension, which would affect the velocity of the wave travel, the conditions of the 2 tests were identical. Tentatively, therefore, the suggestion was advanced that the natural period of oscillation of the insulator string would have an important part in determining the magnitude and frequency of such detached components and that it might under certain conditions be very effective as a dissipator of energy from the main wave. It would be difficult, however, if not impossible, to rely on such action at all times since the tension changes with temperature, hence also the velocity of wave travel changes, and if this mechanical system were to depend upon resonance conditions for its operation, its behavior might be altered materially by slight change in wave velocity.

It is expected that tests made on conductors which are attached to rigid supports would be free from such difficulty and such tests are being continued to determine the relation between energy loss of a traveling wave in the conductor and the tension.

Example 7—Rocking Clamps

Some tests had been made mechanically which indicated that a rocking clamp, i. e., a clamp free to swing in a vertical plane with its axis passing horizontally at right angles through the cable at its point of suspension, would tend to divide the duty imposed by bending, between the 2 ends of the clamp. With restrained motion or large moment of inertia of the clamp this might be modified but the maximum benefit that should be expected would not be more than a 50 per cent reduction of the stress component due to transient curvature.

An opportunity was offered to check the bending at the 2 ends of a clamp on a 795,000-cir mil aluminum-cable steel-reinforced conductor suspended from a flexible string of insulators. The oscillogram, Fig. 10, of such curvatures confirms the earlier mechanical tests very definitely. The recorders have approximately the same sensitivity and the record indicates that the vibration stresses at the 2 ends of the clamp remained in step and with approximately the same amplitude throughout the length of the film.

Under example 4 it was pointed out that there need be no very definite relation between the vibrations in one span and those in the adjacent span. This conclusion was based upon conditions at some distance on either side of the clamp and is consistent with the records discussed in this example.

Example 8—Natural Vibrations

A few records have been obtained due to aeolian vibrations which have been carefully examined to detect characteristics inconsistent with the method of analysis outlined herein. The stresses set up at the end of a rocking clamp have been noted (see Fig. 10) and approximately equal division of the bending is indicated on a number of records.

The duty at the clamp, however, is intensified by the fact that it is affected by vibrations in both adjacent spans. In Fig. 11 is indicated a fairly constant vibration in one span 275 ft from the clamp, while the amplitude at the clamp is alternately reinforced and neutralized by the vibration from the adjacent span.

The latter film (and others of similar type) also indicates a periodic recurrence of a definite sequence of variations in amplitude after an interval which is equal to the length of time required for a wave to travel the length of the span and return. Such a definite repetition can be accounted for on the theory of 2 continuous series of vertical waves traveling in opposite directions along the span and being transmitted and reflected with very little loss of amplitude.

It would seem to be conclusive from this record alone that such an erratic sequence of amplitudes could not be repeated so faithfully after such an interval of time unless the time interval of the traveling wave for the 2 spans were the controlling factor.

This being the case, testing by the use of a pair of traveling waves should be the rational and most direct method of analyzing into its simplest components the problem of vibrational stresses in conductors.

Further Studies

According to this method of analysis the criterion of the effectiveness of any device in mitigating the harmful effects of vibrations might be determined by its effectiveness in (*a*) reducing the ratio of the curvature at the clamp to that in the conductor, (*b*) increasing the rate of dissipation of energy per cycle of operation, and (*c*) decreasing the impact or longitudinal component.

These elements of protection can now be isolated and each treated on its own merit without the delay necessary to carry out endurance tests. Much work, of course, remains to be done to coördinate the

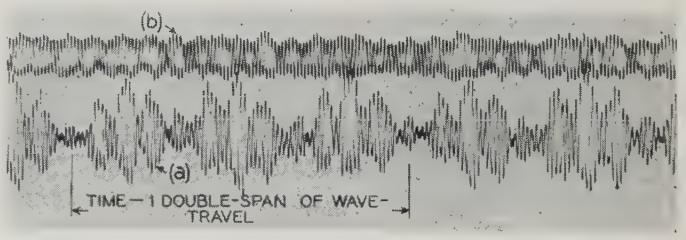

Fig. 11. Curvature records of vibrations in 795,000-cir mil aluminum cable steel reënforced conductors
a. At clamp
b. In span 275 ft from suspension clamp

results with the working stresses and strength of materials to determine what limiting conditions might be set in practice. It has been evident for some years that some factor of safety should be provided to take care of the fatigue due to vibrational stresses but the question of how much has not been determined.

REFERENCES

An extensive bibliography has been prepared by the power transmission and distribution committee of the Institute and has been made available to members interested. It would be difficult to select even a limited number of references and do justice to those who have been actively interested in the problem for several years. This method of analysis, however, appears to be new and if this scheme has been published, even in part, the author and his associates have not been aware of such fact; hence the treatment has been developed directly from fundamentals of physics which are generally accepted and it is trusted will be clear to the reader without supplementary references.

Theory of Multielectrode Tubes

Physical principles underlying the characteristics and performance of multielectrode vacuum tubes are presented in simple form in this paper. The subject is presented from the viewpoint of those having an understanding of the physical principles of the ordinary triode or 3-element tube, but not having a similarly clear understanding of the more complex structures. Detailed analyses of the characteristics of several types of multielectrode tubes are given.

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INTRODUCTION of the 3-electrode vacuum tube into the field of communications and in other applications represented such a tremendous advance over the possibilities of any other known device that, despite some of its rather obvious limitations, it proved entirely adequate for the service required until comparatively recent years. However, with increasing demands made by service requirements for larger power output at higher efficiency, reduced distortion, higher gain, amplification at higher frequencies and greater frequency discrimination, it eventually became necessary to investigate the possibilities of making changes in vacuum tubes enabling them to meet these requirements more satisfactorily. Measures taken to meet this situation have included improvements in the 3-electrode tube that reduce the effects of some of its limitations, and the development of vacuum tubes having more than 3 electrodes.

The purpose of this paper is to present, in simple form, the physical principles underlying the characteristics and performance of multielectrode vacuum tubes. For present purposes, such tubes may be defined as those having more than the 3 electrodes of the conventional triode. The procedure will be to show that the definitions of electrical tube parameters applicable to triodes are, with certain modifications in their interpretation, also applicable to tubes having more than 3 electrodes; and, utilizing the theory of the triode, to analyze the characteristics of a few typical multielectrode structures that illustrate the types of characteristics found in many such tubes. No attempt is made to present new material in the paper or to discuss in detail the many different types of multielectrode tubes now in use. The author has attempted to present the subject from the viewpoint of those readers who have a satisfactory understanding of the physical principles, characteristics, and operation of the triode, but who do not have a similarly clear analysis available for the more complex structures.

Multielectrode tubes may be divided conveniently into 2 classes. In the first class are those the purpose of which is to perform some function that cannot be performed readily by a triode, or which perform some function better by reason of the elimination or reduction of some limitation in triodes. The second class includes those structures in which additional electrodes are introduced to permit them to perform simultaneously more than one function, or to permit them to function in 2 or more ways, depending on the voltages applied to the various electrodes and on the manner of their operation. This paper will deal exclusively with typical structures of the first class.

FUNDAMENTAL DEFINITIONS AND TUBE EQUATIONS

Regardless of the type of multielectrode tube considered, the space current to any electrode may be ex-

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pressed as some function of the voltages applied to the various electrodes. However, in the operation of any multielectrode device, or any section of such a device performing a single function, one usually is concerned with variations in the voltages and corresponding currents of only 2 of the electrodes, the other electrodes being maintained at fixed potentials. One of these 2 electrodes, which usually is maintained at a negative operating potential, is connected to the input circuit and acts as a control electrode. The second of these 2 electrodes, which is maintained at a positive potential with respect to the cathode, acts as an anode or collector of electrons and is connected in the output circuit. Just as in the case of the triode, then, a study of the characteristics of multielectrode tubes is concerned with variations in the current collected by the anode with variations in the potential applied to the control grid.

This anode or plate current may be expressed as a function of the various electrode voltages by the following equation:

$$I_p = f(E_p, E_{g1}, E_{g2}, E_{g3}, \text{etc.}) \tag{1}$$

in which E_p is the operating voltage applied to the output anode or plate, and E_{g1}, E_{g2}, E_{g3}, etc., are the operating voltages applied to the various grids numbered outward from the cathode. The variation in the anode current, neglecting second and higher order terms, is given by

$$dI_p = \frac{\partial I_p}{\partial E_p}dE_p + \frac{\partial I_p}{\partial E_{g1}}dE_{g1} + \frac{\partial I_p}{\partial E_{g2}}dE_{g2} + \frac{\partial I_p}{\partial E_{g3}}dE_{g3} + \text{etc.} \tag{2}$$

The partial differential coefficients in eq 2 have the physical dimensions of conductances and, if these conductances be designated by the letter S with appropriate subscripts, the equation may be written

$$dI_p = S_{pp}\cdot dE_p + S_{p1}\cdot dE_{g1} + S_{p2}\cdot dE_{g2} + S_{p3}\cdot dE_{g3} + \text{etc.} \tag{3}$$

The plate or output anode conductance of a multielectrode tube is defined in the same manner as for the 3-electrode tube. It is the rate of change of plate current with plate voltage, that is, it is the slope of the plate current-plate voltage characteristic at the selected operating point, the potentials of all the other electrodes remaining constant. Under this condition, from eqs 2 and 3

$$\text{Plate conductance} = \frac{\partial I_p}{\partial E_p} = S_{pp} = S_p \tag{4}$$

Obviously, the plate resistance also must be defined in the same manner as in the triode, that is

$$\text{Plate resistance} = R_p = \frac{1}{\dfrac{\partial I_p}{\partial E_p}} = \frac{1}{S_p} \tag{5}$$

In a similar manner, the transconductance from the control grid to the output anode or plate of a multielectrode tube is defined, as it is in the triode, by the rate of change of plate current with variation of the control-grid voltage; that is, it is the slope of the plate current-grid voltage characteristic at the given operating point, the potentials of all electrodes other than the control grid remaining constant.

In conventional screen grid tetrodes and pentodes, the grid next to the cathode is the control grid. Consequently, for such structures, the transconductance is defined from eqs 2 and 3 by

$$\text{Transconductance} = \frac{\partial I_p}{\partial E_{g1}} = S_{p1} \tag{6}$$

In space-charge grid tetrodes and pentodes, the grid next to the cathode is maintained at a fixed positive potential and the second grid acts as the control grid. Consequently, in these and similar structures

$$\text{Transconductance} = \frac{\partial I_p}{\partial E_{g2}} = S_{p2} \tag{7}$$

Similarly, considering the control grid (assumed to be the first grid) and the output electrode of a multielectrode tube, the amplification factor is defined, as it is in the triode, by the ratio of the transconductance to the plate conductance. It is expressed by

$$\text{Amplification factor} = \mu_{pg1} = \frac{\dfrac{\partial I_p}{\partial E_{g1}}}{\dfrac{\partial I_p}{\partial E_p}} \tag{8}$$

Or, assuming that E_{g1} and E_p are varied in such a manner that I_p remains constant, the amplification factor is expressed in the usual form by

$$\mu_{pg1} = -\left.\frac{dE_p}{dE_{g1}}\right]_{I_p} = \text{constant} \tag{9}$$

Combining eqs 5 and 6 with eq 8 gives

$$\text{Transconductance } S_{p1} = \frac{\mu_{pg1}}{R_p} \tag{10}$$

just as in the case of the triode. Exactly similar equations apply if $g2$ is used as the control grid.

Obviously, the currents to the other electrodes in a multielectrode tube may be expressed by functions of the electrode voltages, similar to eqs 1 and 2. The various differential coefficients of these equations define transconductances, electrode resistances, and amplification (or reflex) factors analogous to those just given. Since these quantities are not used in this paper, they will not be given further consideration here. The voltage applied to the control grid will be designated by E_g, regardless of the grid employed for the purpose; and the transconductance (or mutual conductance) and the amplification factor, applying to the control grid and plate, will be designated by S_m and μ, respectively.

If a load resistance, R, is inserted in the plate circuit of a multielectrode tube, and if the potentials of all of the elements other than the control grid and plate are maintained constant, eq 3 reduces to

$$dI_p = S_p\cdot dE_p + S_m\cdot dE_g = \frac{1}{R_p}\cdot dE_p + \frac{\mu}{R_p}\cdot dE_g \tag{11}$$

In this case, the only independent variable is E_g, and E_p varies by reason of the changing potential drop across the external load resistance, R, due to variations in the plate current, I_p, produced by the varying grid potential. Consequently

$$dE_p = -dI_p\cdot R \tag{12}$$

Substituting eq 12 in eq 11 and reducing

$$dI_p = \frac{\mu}{R_p + R}\cdot dE_g \tag{13}$$

For vacuum tubes having curvilinear characteristics, eq 13 applies rigorously, of course, only to infinitesimal variations in I_p and E_g. However, as in the case of the triode, the output from multielectrode tubes may be expressed by a power series in terms of finite voltage variations applied to the elements, and whose coefficients are functions of the static characteristics. If these finite variations in I_p and E_g are designated by i_p and e_g, respectively, the output current is expressed to the first order by

$$i_p = \frac{\mu e_g}{R_p + R} \tag{14}$$

which is identical with the equation expressing the output current from a triode.

Letting e_p represent the variable voltage across the load resistance, R, the voltage amplification is given by

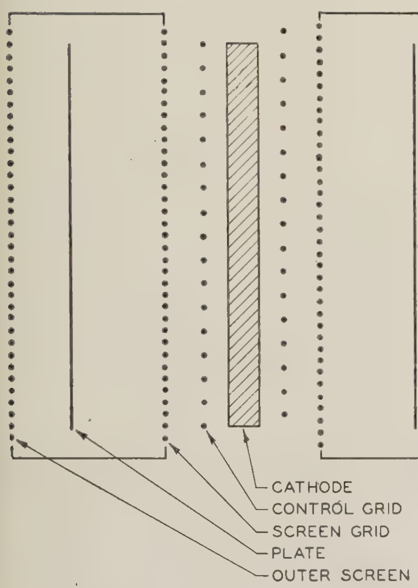


Fig. 1. Schematic diagram showing the arrangement of electrodes in a screen grid tetrode

$$A_v = \frac{e_p}{e_g} = \frac{i_p \cdot R}{e_g} = \frac{R}{R_p + R} \cdot \mu \tag{15}$$

It may also be written in the following form which will be found useful later

$$A_v = \frac{R_p \cdot R}{R_p + R} \cdot \frac{\mu}{R_p} = \frac{R_p \cdot R}{R_p + R} \cdot S_m \tag{16}$$

It should be emphasized, perhaps, that the electrical parameters of multielectrode tubes and the output current, as defined by the foregoing equations, are subject to the condition that the voltages applied to all of the electrodes other than the plate and control grid are maintained constant. The satisfactory operation of multielectrode tubes in circuits also usually requires that this condition be fulfilled. It requires that the impedance to alternating current components in each of these circuit branches be very low. This is accomplished in practice by connecting these electrodes to ground, so far as alternating currents are concerned, through reasonably large capacitances.

From the foregoing analysis it is apparent that, with proper interpretation, the definitions of plate resistance, transconductance, and amplification factor applicable to triodes are also applicable to multielectrode tubes; in addition, the same expressions for output current and voltage amplification are applicable. This follows from the fact that these quantities are expressed in terms of the differential coefficients of the static characteristics, that is, they depend only upon the slopes of these characteristics at the given operating voltages and not upon their form. However, as will appear later, the difference in the shape of the static characteristics of multielectrode tubes from those of triodes is very important in determining great differences not only in the magnitude of the electrical parameters, but also in the character and amount of distortion resulting when the tubes are operated under conditions such that large portions of the characteristics are traversed.

In multielectrode tubes, as well as in triodes, the total space current drawn from the cathode is determined by the extent to which the resultant field, due to the electrodes, overcomes the opposing field produced by space charge. While space charge extends throughout the interelectrode space, it is relatively so much more dense in regions of very low electron velocity that, as a first approximation, its effect usually may be neglected in other regions. Except in space-charge grid tubes and a few other special tubes, the only important space charge region is confined to a relatively thin sheath near the cathode surface. Consequently, in such structures the total space current is determined largely by the extent to which the resultant positive field due to the electrodes neutralizes the negative field near the cathode surface produced by space charge. An appreciation of this fact is essential to a clear understanding of the characteristics of multielectrode tubes.

Screen Grid Tetrode

Utilizing the simple theory of triodes, which has been shown to be applicable to multielectrode tubes also, the characteristics of a multielectrode tube will be analyzed next. For this purpose the screen grid tube is chosen, since it admirably illustrates the type of characteristics found in several types of multielectrode tubes.

The objective in this case is to reduce the direct capacitance between the plate and control grid through which energy is fed back from the plate to the input circuit. This is accomplished by inserting an electrostatic shield between the plate and control grid of what otherwise would be a 3-electrode tube. The condition that such a screen must allow an electron stream to flow through it to the plate, is satisfied by making it of fine mesh or in the form of a finely wound grid structure. To be effective, it must be maintained at some constant potential with respect to ground.

The arrangement of the electrodes in such a tube is shown diagrammatically in Fig. 1. The screen structure outside the plate is added for the purpose of completing the electrostatic isolation of the plate and its leads from the grid, thus reducing the ca-

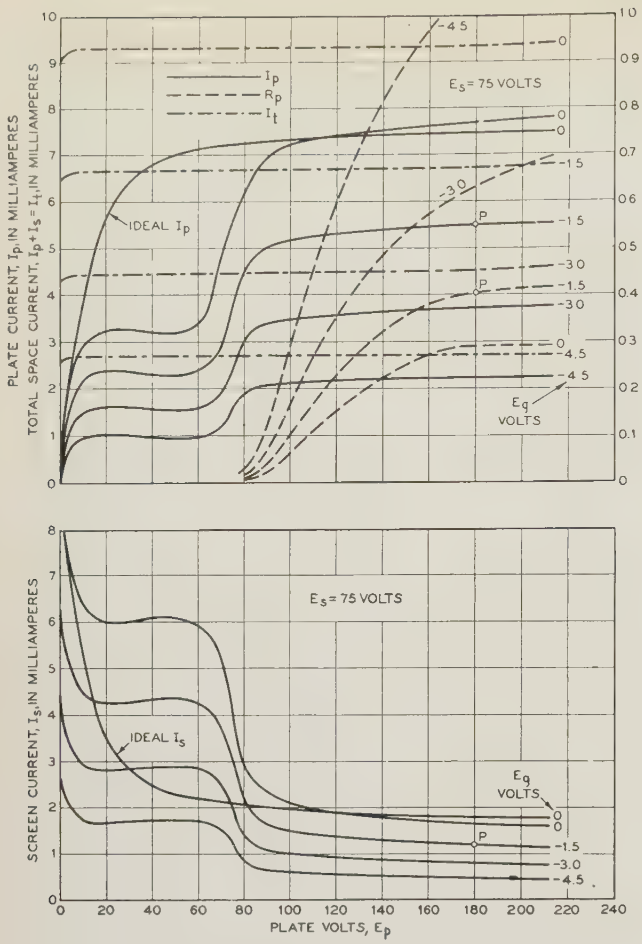


Fig. 2. Characteristics of a screen grid tetrode

The curves show the plate current, I_p, screen current, I_s, total space current, $I_t = I_p + I_s$, and plate resistance, R_p, as functions of the plate voltage. Control-grid voltage, E_g, is indicated on the curves. Screen voltage, E_s, is maintained constant at 75 volts throughout

pacitance between these 2 elements to the lowest practicable value. This outer screen is of no further concern, since it has no effect on the static characteristics of the tube. The usual characteristics of a typical screen grid tetrode are shown in Figs. 2, 3, and 4. In this case, as is usual in screen grid tubes, the shielding is very complete, reducing the direct capacitance between the plate and control grid to a few thousandths of what its value would be in the absence of the screen.

First, the characteristics of Fig. 2 will be considered. Since the direct capacitance between the plate and the control grid, $g1$, is extremely small, the electric field in the immediate vicinity of the latter, produced by any potential on the plate, also must be extremely small. The cathode is electrically even more remote from the plate than the control grid, because it not only is shielded from the former by the screen grid, but also has some additional shielding from the control grid. Consequently, the field produced by the plate at points between the cathode and control grid is smaller even than the field produced at the control grid and, hence, is negligibly small. Since, as previously discussed, the total space current is determined almost wholly by the field very near the cathode surface, the plate in this case can have practically no effect on the total space current drawn from the cathode. This is shown by the curves giving the total space current, I_t, in Fig. 2. These curves are seen to be so flat as to be almost entirely independent of variations in the plate voltage.

The plate, then, in a screen grid tube plays an essentially passive rôle which is to collect those electrons that succeed in passing through the screen. The remainder of the space current is collected by the screen, the sum of the plate and screen currents remaining nearly constant with changes in plate voltage.

There is nothing in the theory of the triode by which to determine the ratio in which space current divides between 2 or more positive electrodes in a multielectrode tube. As a rough approximation, one might assume that when their potentials are nearly equal the currents to the plate and screen would be proportional to the ratio of the area of the openings in the screen to the area subtended by its lateral wires. Also, it might be expected that this ratio would increase slightly with increasing voltage of the plate with respect to the screen, because of a tendency of the plate to pull more electrons through the screen. This effect should be less for very fine mesh screens than for coarse ones.

From this simple theory, one would expect the plate current-plate voltage characteristics to be very flat for plate potentials higher than the screen potential. Consequently, the plate conductance given by

$$S_p = \frac{\partial I_p}{\partial E_p} = \frac{1}{R_p}$$

is a very small quantity; and the plate resistance, given by

$$R_p = \frac{1}{\dfrac{\partial I_p}{\partial E_p}}$$

is a very large quantity compared with its value in triodes, and increases with the fineness of mesh of the screen grid. The plate current curves of Fig. 2 are seen to be in general accord with this simple theory at the higher values of plate voltage, although they are not quite as flat as might be expected from the theory. This, and the rapid falling off in the vicinity of 100 volts, will be discussed later.

Taken alone, the extremely high resistance of a screen grid tube would seem to be a very serious disadvantage. From eq 14, the tube may be considered as analogous to a generator the electromotive force of which is μe_g and the internal resistance of which is R_p, working into an external load resistance R—a generator with extremely high internal resistance. Why this is not fatal to the usefulness of the tube will be pointed out later.

While the plate current in a screen grid tube is nearly independent of plate voltage for values of the latter higher than the screen potential, this obviously cannot hold at low values of plate voltage. At zero plate voltage, the plate current must be zero. At this point the screen collects the entire space current and $I_s = I_t$. As the plate potential increases from zero, the plate current would be expected to rise

rapidly, with a corresponding drop in the screen current, as the plate collects more and more of the electrons passing through the screen. However, 2 factors tend to prevent an abrupt rise in the plate current to its nearly constant value when the plate becomes slightly positive. The first of these is space charge in the region closely adjacent to the plate produced by the electrons that pass through the screen, reach zero velocity in the region adjacent to the plate, and return to the screen. Some of them may perform several oscillations to and fro through the screen before being captured by it. This space charge effect is largely masked by the more important second factor which is the deflection of the majority of the electrons from their normal paths by the intense electric fields about the lateral wires of the screen. This results in large differences in the components of velocity of the electrons normal to the surface of the plate and, consequently, in the distance to which they approach the plate in their trajectories before being turned back to the screen. As a result, the plate must become positive by several volts with respect to the cathode before it captures substantially all of the electrons that pass through the screen.

From this simple theory, the plate current and screen current curves would be expected to have the form shown by the ideal curves of Fig. 2. Obviously, the screen current curves must be complementary to the plate current curves since the sum of the 2 currents is substantially constant.

The difference between these ideal curves and the actual characteristics, in the region extending from a few volts to potentials somewhat higher than the screen voltage, is attributed to the phenomenon of secondary electron emission. When electrons strike a metal surface with velocities equivalent to more than a few volts, other electrons, known as secondary electrons, are liberated from the surface. The number of electrons so liberated varies not only with the velocity of the primary bombarding electrons, but also with the character of the metal surface, the amount of adsorbed gases and other materials on the surface, and other factors. The number of such electrons leaving the surface may even exceed the number of primary electrons striking it, in which case the net current to the metal surface is negative. The velocity of the secondary electrons varies greatly. A very few have velocities approaching that of the primary electrons. The great majority, however, have low velocities equivalent to only a few volts.

In the screen grid tube, an appreciable number of secondary electrons is liberated from the plate at potentials between 5 and 10 volts, and they increase in number with plate voltage. For plate potentials lower than the screen potential, in this case 75 volts, the secondary electrons from the plate are drawn to the screen, thus increasing the screen current by the amount the plate current is decreased. When the plate reaches a potential equal to that of the screen, secondary electrons no longer can escape from the plate to the screen, except those emitted with appreciable velocities; consequently, the plate current rises rapidly to its normal value.

At plate potentials higher than the potential of the screen, secondary electrons emitted from the latter are drawn to the plate. Consequently, in this region the plate current is slightly higher than it would be in the absence of secondary electron emission from the screen. The gradual rather than abrupt rise in the plate current curves at 75 volts is attributed primarily to the distribution of velocities with which the secondary electrons are emitted; to a lesser extent, it is dependent also on the combined effects of space charge, intensity, and distribution of the field at the surface of the screen wires.

Normal operating conditions for the screen grid tube the characteristics of which are shown in Fig. 2 are: E_p = 180 volts, E_s = 75 volts, and E_g = -1.5 volts. At this operating point P in Fig. 2, the plate current is 5.5 ma and the plate resistance is 400,000 ohms. The operating range is confined to the flat portion of the characteristics. If the tube is operated with plate voltage swings sufficiently large that the instantaneous values of the plate potential extend into the region of rapidly falling plate current, serious distortion of the output results. This is a serious limitation in screen grid tetrodes, because it requires that the operating plate potential be much higher than the screen potential. How this limitation may be removed by the introduction of an additional electrode in the tube will be shown later.

Curves showing the variation of plate resistance with plate voltage are shown in Fig. 2. The plate resistance decreases with plate voltage, falling off

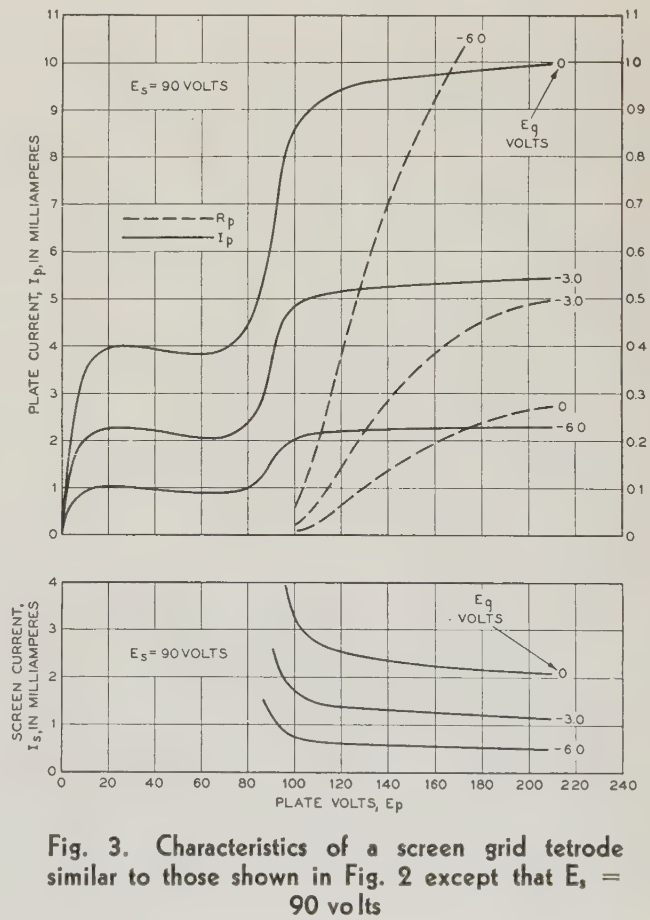


Fig. 3. Characteristics of a screen grid tetrode similar to those shown in Fig. 2 except that E_s = 90 volts

very rapidly as the plate voltage approaches the screen voltage. The ordinates of the plate resistance curves give a measure of the flatness of the plate current curves. That the latter are not as flat as the total-space-current curves, thus resulting in values of plate resistance approaching infinity, is attributed to 2 factors: secondary electron emission from the screen, and an increasing ratio of plate current to screen current with increasing plate voltage. The increasing percentage of the primary space current drawn to the plate with increasing plate voltage is an involved and undetermined function of several factors including: the ratio of the openings in the screen grid to the total conducting area subtended by it, the intensity and distribution of the field at the screen grid, the velocity and directional distribution of the electrons arriving at the screen grid, and space charge effects in its vicinity.

Thus, there is the interesting situation in screen grid tubes that, for any given set of operating voltages, the magnitudes of the plate resistance and amplification factor are determined largely by factors not directly determined by the geometry and design of the tube. This is quite different from triodes in which the plate resistance and amplification factor both are determined directly by geometrical dimensions and the arrangement of the electrodes.

Obviously, the number of electrical parameters in vacuum tubes increases rapidly with the number of electrodes. The curves of Fig. 2, which correspond to the usual plate current-plate voltage characteristics for a triode, were obtained with the screen maintained at a constant potential of 75 volts as a fixed parameter. To obtain a complete charting of the characteristics would require several such families of curves taken with different screen voltages. One such additional family of characteristics, in which E_s is maintained at 90 volts, is shown in Fig. 3.

Since the plate in a screen grid tube has practically no effect on the total space current, so far as consideration of the latter is concerned one may regard the plate as being removed from the structure and consider only the remaining elements. The cathode, control grid, and screen then may be regarded as constituting an ordinary triode. By maintaining the screen at a positive potential, it is enabled to perform the function usually performed by the plate of a triode, *viz.*, that of supplying the positive field necessary to produce the flow of space current against the opposing resistance due to space charge. This function does not interfere with its screening action, so long as its potential is not allowed to vary. In fact, there is an actual gain in efficiency, as will be shown later, in having the electrode that provides the main driving field for the space current maintained at a fixed potential instead of varying over the operating cycle as it must in the triode.

Usual design principles and equations applicable to triodes are also applicable to screen grid tetrodes. By making the spacings between the electrodes small,

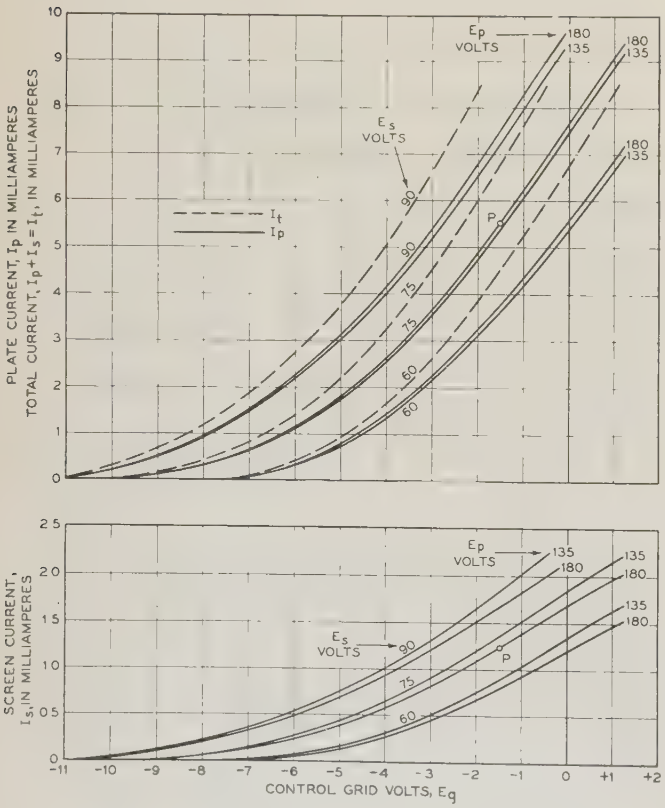


Fig. 4. Characteristics of a screen grid tetrode

Plate current, I_p, screen current, I_s, and total space current, I_t, as functions of the control-grid voltage, with various values of plate voltage and screen voltage as parameters

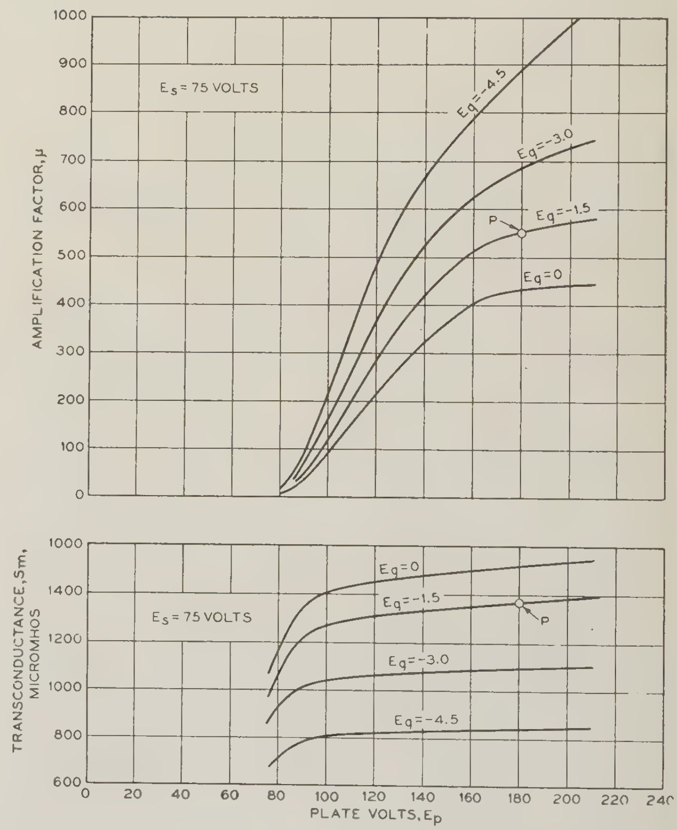


Fig. 5. Amplification factor and transconductance of a screen grid tetrode as functions of the plate voltage

particularly that between the cathode and control grid, a high transconductance can be obtained. Using the subscript t to designate total space current, the transconductance is given by $S_t = \frac{\partial I_t}{\partial E_g}$ and has the same value as that for a triode of the same dimensions. Let f represent the fraction of the total space current that passes through the openings in the screen and is collected by the plate, which is assumed to be at a higher potential than the screen. By proper design, f can be made large, say from 0.7 to 0.9, in the normal operating range. The transconductance from the control grid to the plate is given by

$$S_m = \frac{\partial I_p}{\partial E_g} = f \cdot \frac{\partial I_t}{\partial E_g}$$

which is 0.7 to 0.9 of the normal value of transconductance for the 3-electrode tube.

The amplification factor, μ, for the tetrode, is given by

$$\mu = \frac{\dfrac{\partial I_p}{\partial E_g}}{\dfrac{\partial I_p}{\partial E_p}} = S_m \cdot R_p \qquad (17)$$

Since the transconductance, S_m, has a value not greatly different from the normal value for a triode, and since R_p is very large, μ, which is proportional to R_p, also must be very large. Referring to eq 14 and its analogy with the generator equation, it may be seen that, despite the fact that the screen grid tube considered as a generator has a very high internal resistance, it gives normal output because it is provided also with a very large electromotive force, μe_g.

From this analysis of the characteristics of the screen grid tube, based upon the simple theory of triodes, one would expect that families of characteristics corresponding very closely with those of ordinary triodes would be obtained if the total space current, or the plate current, were plotted as functions of the control grid voltage and screen grid voltage, with the plate maintained at any fixed potential higher than the screen potential. It would be expected further that the family of curves showing total space current would remain practically invariant with variations in plate voltage. The plate current family of characteristics should show only small variations with plate voltage (so long as E_p is higher than E_s), depending on the magnitude of the change in the ratio of I_p to I_s.

Families of such characteristics are shown in Fig. 4. They are seen to correspond very closely indeed with similar characteristics for a triode. The I_t curves vary so little with plate voltage that the families of characteristics taken at E_p = 135 volts and E_p = 180 volts, coincide within the breadth of the curves. The plate current curves show a small variation with E_p, as was discussed previously.

In Fig. 5 the transconductance and amplification factor are shown as functions of the plate voltage for 4 different values of grid bias and with the screen potential maintained constant at 75 volts. At the normal operating point P, the transconductance is 1,375 micromhos and the amplification factor is 550.

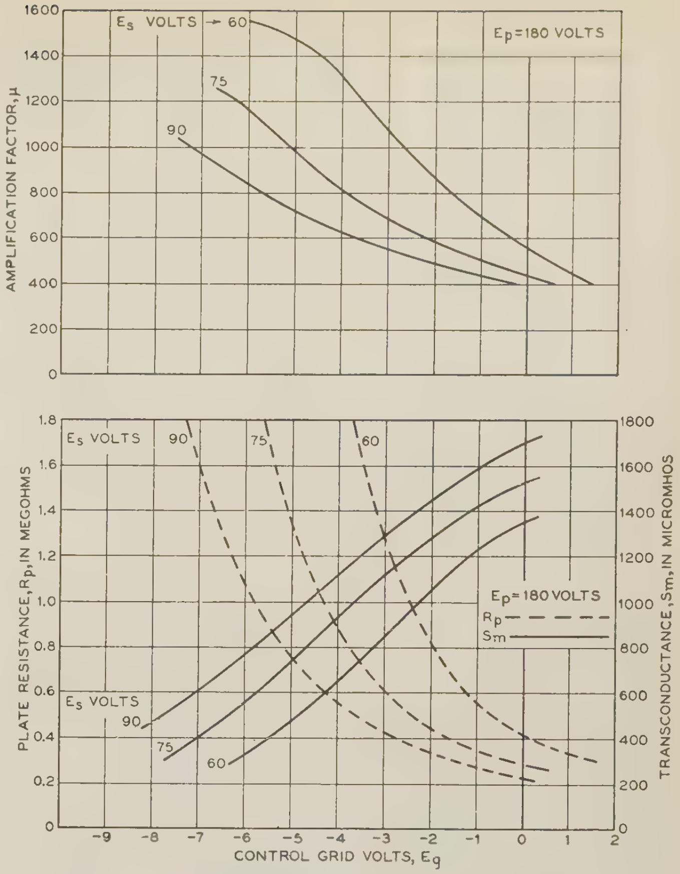


Fig. 6. Amplification factor, transconductance, and plate resistance of a screen grid tetrode as functions of the control-grid voltage

The shape of these curves is typical of that for screen grid tubes and pentodes. Throughout the normal operating range, the transconductance curves have about the same degree of flatness as the plate current curves. This is to be expected from consideration of the plate current curves of Fig. 4. Since these curves change only slightly with variations in plate potential, their slopes or transconductance values also change but slightly. The amplification factor curves are very similar in form to the plate resistance curves of Fig. 2. This follows at once from eq 17, for since S_m remains nearly constant with variations in E_p, μ must vary in the same manner as R_p.

In Fig. 6 the transconductance, plate resistance, and amplification factor are shown as functions of grid voltage for 3 different values of the screen voltage and with the plate voltage maintained constant at 180 volts. These curves are also typical of those found for several multielectrode tubes. The transconductance curves agree in form with those for a triode, as would be expected from the plate current curves of Fig. 4. The plate resistance curves are similar in form to those for a triode, but rise more rapidly with increasing negative grid bias. The amplification factor curves, however, are entirely different in form from those for a triode, since they rise with increasing negative grid bias, whereas in triodes the amplification factor decreases with increasing negative grid bias. The reason for this difference is that the plate resistance in many multi-

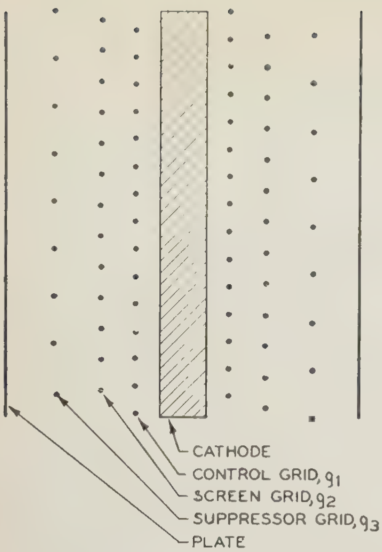


Fig. 7. Schematic diagram showing the arrangement of electrodes in a power pentode

electrode tubes, over the normal range of operation, increases more rapidly with decreasing plate current than in triodes. At sufficiently large negative values of grid bias and very low plate currents, the amplification factor curves frequently reach maxima and then fall rapidly as they do in triodes.

In the operation of triodes as voltage amplifiers, it is usually possible to have the external load resistance large with respect to the plate resistance. Consideration of eq 15 shows that this results in a voltage amplification ratio approaching the amplification factor. In the operation of screen grid tubes and conventional pentodes as well, which have high plate resistances, it is usually necessary that the load resistances be much smaller than the plate resistances. This limitation is imposed by circuit coupling requirements and sometimes by restrictions on the permissible harmonic content in the power output. This limitation results in an amplification ratio that is much smaller than the amplification factor; but even so, a considerably higher amplification ratio usually can be obtained than with triodes. This is apparent from consideration of eq 16 which may be written in the form,

$$A_v = S_m \cdot \frac{R}{1 + \dfrac{R}{R_p}} \tag{18}$$

Since in screen grid tubes and pentodes R/R_p is small, the voltage amplification is given approximately by

$$A_v = S_m \cdot R \tag{19}$$

Now, in a comparable triode the transconductance will have a value comparable with S_m, and it may be assumed that a load resistance could be used comparable with R. However, the ratio R/R_p for the triode is not small and may be greater than unity. Hence, from eq 18, the amplification obtained with the triode is correspondingly smaller.

It has been shown that the presence of the electrostatic screen in the screen grid tetrode results in a high plate resistance and a high amplification factor, but that the ratio of μ to R_p (transconductance) remains normal. Such tubes yield high amplification and, with suitable associated circuits, are relatively free from feed-back; but they are limited in their range of operation because of the fold in the plate current-plate voltage characteristics resulting from secondary emission from the plate.

Power Pentodes

In order to deliver a large power output, a vacuum tube must be capable of large variations in plate current and plate voltage from their normal operating values. Both of these conditions are fulfilled by the power pentode. The arrangement of the electrodes, shown schematically in Fig. 7, corresponds to that in a screen grid tube except that an additional grid, $g3$, is inserted between the plate and screen grid, $g2$. As in the screen grid tube, the first grid, $g1$, has a negative voltage applied to it and acts as the control element. The second grid, $g2$, is maintained at a fixed positive potential, E_s, and provides the main driving field for the space current.

As in the screen grid tube, the total space current is determined almost wholly by the geometrical dimensions and spacings of the cathode, $g1$ and $g2$, and by the voltages applied to these electrodes. Consequently, in the design of this portion of the structure, the same considerations apply as in the design of an ordinary triode to deliver large power

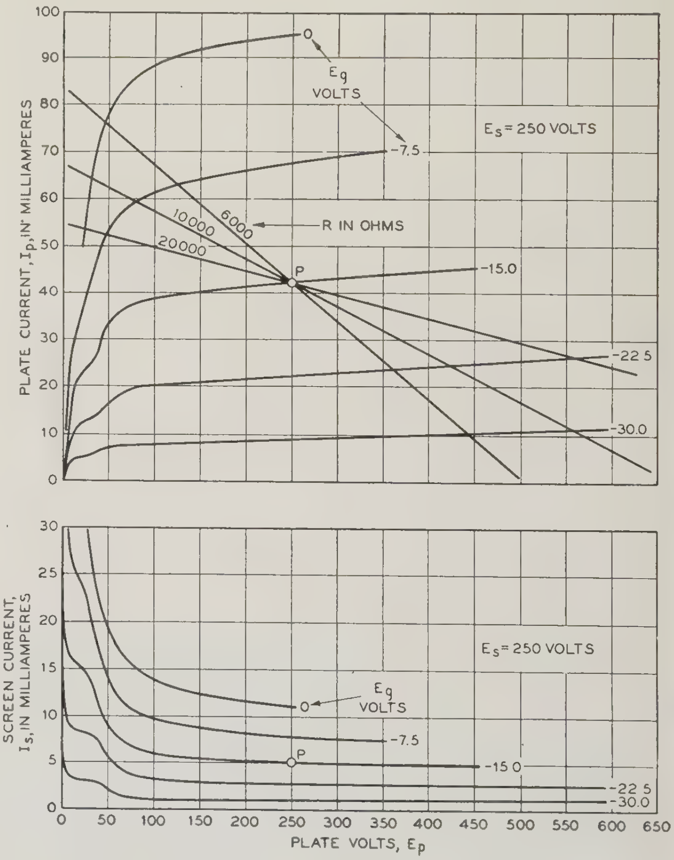


Fig. 8. Characteristics of a power pentode

Plate current, I_p, and screen current, I_s, as functions of the plate voltage with various values of the control-grid voltage, E_g, as parameters. Screen voltage, E_s = 250 volts throughout. Load lines are shown for resistance loads of 6,000, 10,000, and 20,000 ohms

output. By making the inner grid comparatively coarse and by designing the second grid to operate at comparatively high potentials, a structure having a low amplification factor is obtained which draws a large space current from the cathode at a control grid bias sufficiently negative to permit relatively large swings of the control grid voltage. In pentodes designed to operate at low frequencies, screening between the plate and control grid is unimportant; hence, the second grid can be comparatively coarse thus permitting as large a portion as possible of the space current to pass through it to the plate.

To permit the largest possible swings in plate voltage, it is necessary to remove the "fold" in the plate current characteristics, caused by secondary electrons emitted from the plate. This is accomplished by the insertion of a third grid, $g3$, between the plate and second grid, $g2$. This grid, known as a suppressor grid, must be maintained at a lower potential than the lowest instantaneous potential reached by the plate, and is usually maintained at the cathode potential by connecting it to the cathode inside the tube. The suppressor grid exerts a retarding force on the primary electrons flowing toward it from the cathode, but, because of its coarse structure, all but a small fraction succeed in passing through it and are accelerated again, finally reaching the plate with the same velocity they would have if the suppressor grid were absent. On the other hand, secondary electrons emitted either by the plate or screen grid find themselves in a retarding field, which they are unable to traverse because of their low velocity, and are constrained to return to the electrode from which they came.

Plate current-plate voltage characteristics and screen current-plate voltage characteristics for a power pentode of the indirectly heated cathode type, are shown in Fig. 8. The secondary emission "fold" in the characteristics is almost completely eliminated by the suppressor grid.

The effectiveness of the suppressor grid is shown by the characteristics of Fig. 9. These curves were obtained from a tube of the same type as that for which the characteristics are shown in Fig. 8. One set of curves was obtained with the suppressor grid operating in the normal manner. The other curves were obtained with the suppressor grid tied to the screen grid and maintained at a positive potential of 250 volts. In this latter case, the number of secondary electrons escaping from the plate is practically the same as if the suppressor grid were removed from the tube. The presence of the suppressor grid not only permits the plate to swing to very much lower potentials than otherwise would be possible, but also permits the plate and screen to operate at the same potential, which is 250 volts in this case.

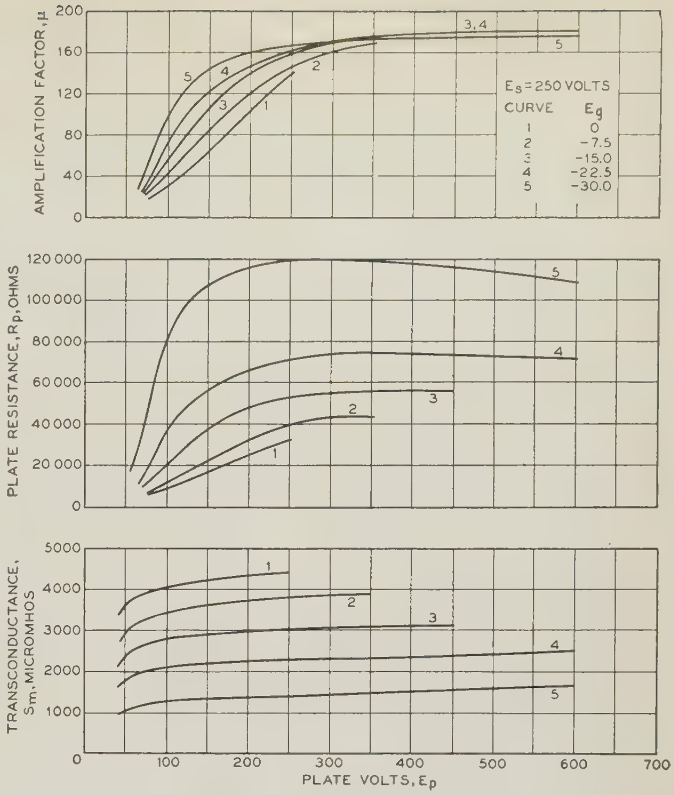


Fig. 10. Amplification factor, plate resistance, and transconductance of a power pentode as functions of the plate voltage, with various values of control-grid voltage as parameters

Screen voltage, E_s, is maintained constant at 250 volts

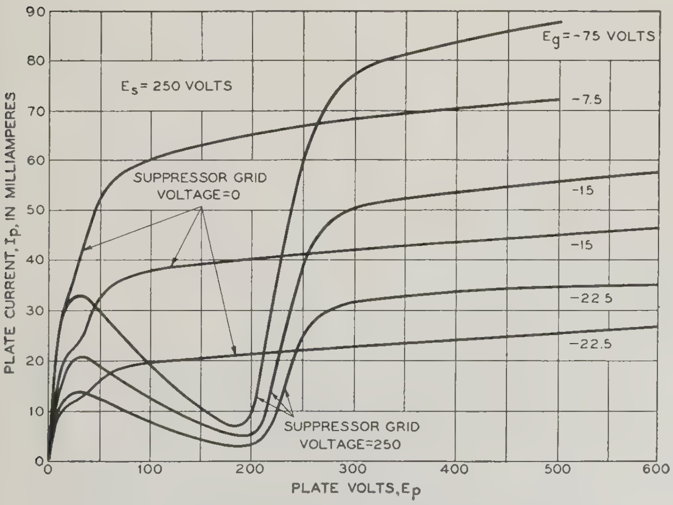


Fig. 9. Curves showing the effect of the suppressor grid in a power pentode

The characteristics of Fig. 8 closely approach the form that would be expected from simple theory. As is usual with power pentodes, the curves are not quite as flat as those for screen grid tubes. This is because of the more open character of the grids which permits the plate to have a slightly greater effect on the magnitude of the space current. This is evidenced also by the tendency of the curves to turn up at the higher plate voltages.

The normal operating point for this tube is at point P in Fig. 8, at which the plate and screen potentials are both 250 volts and the control grid potential is -15 volts. Under these conditions, the average characteristics are: $I_p = 42$ ma, $I_s = 5$ ma, $\mu = 156$, $R_p = 52{,}000$ ohms, and $S_m = 3{,}000$ micromhos.

Curves showing the amplification factor, μ, the plate resistance, R_p, and the transconductance, S_m,

for several different values of grid bias, are shown in Fig. 10. They correspond in general form to those shown in Figs. 3 and 5 for the screen grid tube. The maxima in some of the plate resistance curves result from the fact that the corresponding plate current curves turn up at the higher plate potentials and thus have points of inflection.

In Fig. 11, the plate current is shown as a function of control grid voltage for various values of the plate voltage, with the screen potential constant at 250 volts. The curves are very similar to corresponding ones for the screen grid tube shown in Fig. 4. Here, curves are included at such low plate voltages that a large falling off in plate current occurs.

In Fig. 12, the power output in watts, and the second and third harmonics, expressed in decibels below the fundamental, are shown as functions of peak volts for a sinusoidal input applied to the grid. These data were obtained under the normal operating conditions previously given, and with the indicated load resistances. Since the curves are typical in form of those obtained in several types of multi-electrode tubes, it will be of interest to examine them in some detail.

Except at the higher inputs, the power output increases continuously with load resistance over the load range considered. This is to be expected, since the highest load resistance of 12,000 ohms is much smaller than the plate resistance of the tube, which is 52,000 ohms. For small inputs, the maximum power output would be obtained, as it is in triodes, when the load resistance is equal to the plate resistance of the tube. The decrease in power output with increasing load resistance, at the higher inputs, results from the progressive turning over of the dynamic characteristics as shown by the curves of Fig. 11.

The second harmonic decreases continuously with increasing load resistance at small inputs. At large inputs, it decreases at first, then increases with

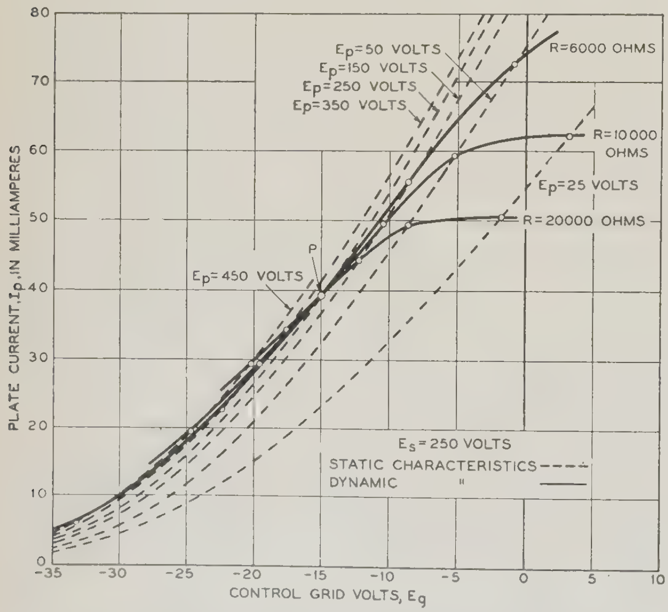
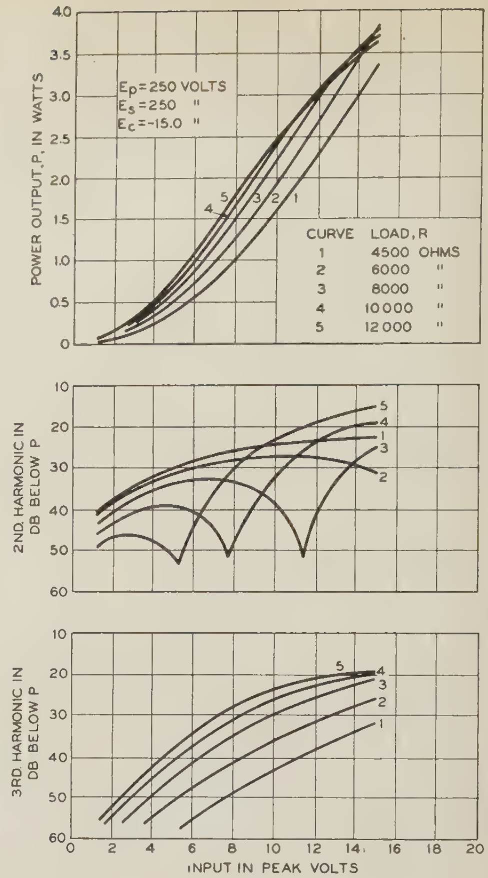


Fig. 11. Plate current-grid voltage characteristics of a power pentode, with dynamic characteristics for resistance loads of 6,000, 10,000, and 20,000 ohms

Fig. 12. Characteristics of a power pentode

Power output, P, in watts, second and third harmonics in decibels below the fundamental, as functions of the peak input when a sinusoidal voltage is applied to the control grid



increasing resistance. At very low resistances, the second harmonic increases continuously with input. At higher load resistances, it rises to a broad maximum, then falls to a very sharp minimum, after which it again rises rapidly with increasing input. The explanation of these phenomena will be given later.

The third harmonic increases continuously both with increasing input and with increasing load resistance. At load resistances that are small compared with the plate resistance of the tube, it rises to a higher level than the second, over a certain range of input. Relatively high levels of third harmonic are characteristic of pentodes, screen grid tubes, and also of some other types of multielectrode tubes. For example, from the curves of Fig. 12, with a load resistance of 6,000 ohms and an input of 15 peak volts, the power output is 3.8 watts with the volume level of the second and third harmonics 31 db and 26 db, respectively, below that of the fundamental. At an input of 10 peak volts, the volume level of the second harmonic rises to 27 db and of the third harmonic falls to 36 db below that of the fundamental.

These results are quite different from those obtained with triodes where the third harmonic is, in general, 10 db or more below the second. Furthermore, in triodes, both the second and third harmonics decrease continuously, as a rule, with increasing load resistance. There are exceptions to this, however, where the third harmonic curves show minimum points or cusps, similar to those shown by the second harmonic curves for pentodes.

The reason for the relatively large harmonic content in the output of pentodes is apparent from consideration of the load lines drawn through the operating point P in Fig. 8. At the lower values of plate voltage, the load lines cut across the rapidly descending portions of the plate current characteristics. This effect is more marked and begins at more negative values of grid bias as the load resistance increases and the slope of the load lines becomes correspondingly less. The effect of this is to produce current variations through the external load resistance that are not proportional to the variations in grid voltage, thus resulting in distortion of the output.

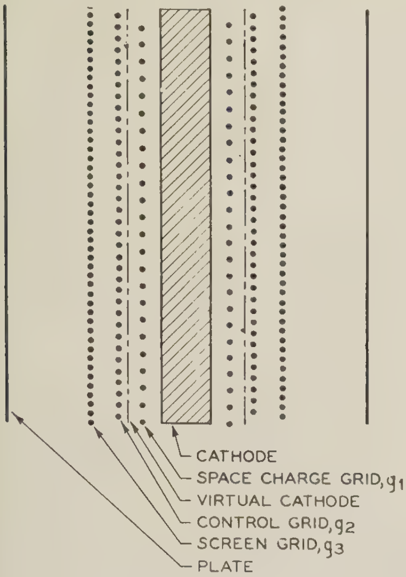


Fig. 13. Schematic diagram showing the arrangement of electrodes in a space-charge-grid pentode

The character of the distortion is made clearer by reference to the dynamic characteristics of Fig. 11, for resistance loads of 6,000, 10,000, and 20,000 ohms. All the curves show a flattening out at the top which increases progressively with load resistance. It readily is shown that such dynamic characteristics, having points of inflection at which the curvature changes sign, give rise to peculiarities in the harmonic output.

If such a characteristic be expressed by a power series in terms of grid voltage variations from the operating point P, there usually is found a relatively large contribution by third and higher odd-power terms the coefficients of which are predominantly negative in sign. Since odd-power terms yield odd harmonics, this accounts for the relatively high levels of third harmonic at input voltages sufficiently large that the flat portion of the characteristic is traversed. However, positive and negative signs are about evenly divided among the coefficients of the even-power terms, which yield even harmonics. At some value of the input voltage, which varies with the load resistance, the contributions to the second harmonic by positive and negative terms are approximately equal, resulting in a very small value of this harmonic. This accounts for the cusps in the second harmonic curves of Fig. 12. For inputs less than the value at the cusp, the contribution of positive terms (largely the second-power term) prevails over that of negative terms, while at higher inputs the reverse is true. Consequently, there is a reversal in the phase of the second harmonic at the cusp.

If the point of inflection were at the operating point P and, if the dynamic characteristic were symmetrical about P, then only odd-power terms would appear in the equation of the curve. Consequently, in this special case, even harmonics would vanish from the output and only odd harmonics would remain.

Plate circuit efficiency of pentodes is higher than that usually found in triodes. The underlying physical reasons for this difference are as follows: In the triode, the plate simultaneously performs 2 functions. First, it is the element in the output circuit whose fluctuating potential is impressed across the load resistance. Second, assuming that the grid potential is not positive, the plate is the only positive electrode providing the necessary driving force for the space current. These 2 functions militate against each other to a certain extent, for, as is evident from consideration of the dynamic characteristic of either a triode or a pentode, the plate voltage reaches its minimum value at the instant when the plate current reaches its maximum value. This minimum voltage, which must be sufficiently large to draw the peak current through the tube, is a very

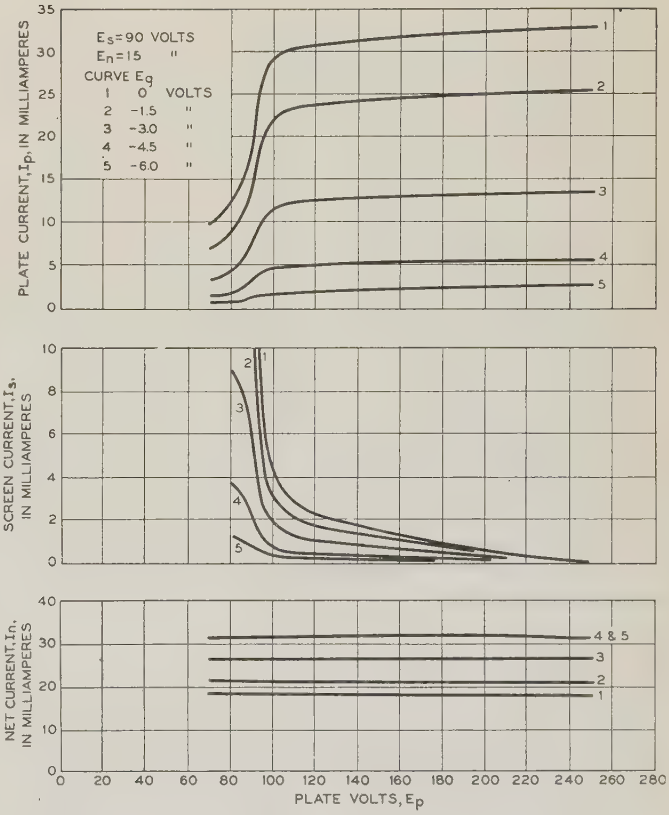


Fig. 14. Characteristics of a space-charge-grid pentode

Plate current, I_p, screen current, I_s, and net (space-charge-grid) current, I_n, as functions of the plate voltage with the indicated values of control-grid voltage as parameters. Screen-grid voltage, E_s = 90 volts. Net (space-charge-grid) voltage, E_n = 15 volts

Table I—Comparative Data for Typical Triodes and Pentodes

	Triodes			Pentodes		
	A	B	C	D	E	F
Plate voltage, E_p	200	250	325	180	250	250
Screen voltage, E_s				180	250	250
Grid voltage, E_g	−45	−50	−68	−18	−16.5	−15
Plate current, I_p, ma	45	34	60	14.5	34	42
Screen current, I_s ma				2.8	6.5	5
Transconductance, S_m, micromhos	2,810	2,175	5,200	1,050	2,200	3,000
Amplification factor, μ	2.9	3.5	3.8	105	220	156
Plate resistance, R_p, ohms	1,030	1,610	730	100,000	100,000	52,000
Load resistance, R, ohms	2,060	3,900	2,750	12,000	7,000	6,000
Input, peak volts	45	50	68	18	16.5	15
Power output, watts	1.9	1.9	7.8	1.2	3.0	3.8
Second harmonic, %	7.4	5.7	5.0	5.0	2.3	2.8
Third harmonic, %	0.7	1.2	1.1	7.5	6.6	5.0
Total harmonic, effective %	7.45	5.9	5.1	9.0	7.0	5.7
Plate efficiency, %	21	22	40	46	35	36
Plate-grid capacitance, $\mu\mu f$	12	7.2	20	1.2	0.8	0.2
Plate-ground capacitance, $\mu\mu f$	3.2	3.0	5.5	7.8	8.5	15
Grid-ground capacitance, $\mu\mu f$	6.8	4.5	9	6.4	8.4	9

substantial fraction of the operating plate voltage, particularly when the latter is comparatively low.

In pentodes and in some other multielectrode tubes, the positive grid, maintained at a constant voltage, provides the necessary driving force for the space current, thus relieving the plate from performing this function. Consequently, the plate is free to swing to lower voltages than otherwise would be possible, which results in a corresponding increase in efficiency.

In Table I, similar data are shown for typical pentodes and triodes. While the triodes and pentodes are not directly comparable with each other, the data are indicative of the differences between the 2 types of tubes. The chief differences between pentodes and triodes may be summarized as follows:

1. Pentodes yield higher gain and require correspondingly lower input voltages to drive them.

2. Pentodes have much higher amplification factors and plate resistances than triodes. The latter constitutes a handicap in coupling the tube to its circuit, particularly if transformer coupling is employed.

3. Pentodes yield high power output, generally at higher plate efficiency than triodes.

4. The harmonic content in the output of pentodes is high, the third harmonic being particularly high compared with its level in triodes. This requires that pentodes work into load impedances that are very low compared with the plate resistance. Ratios of R to R_p of $^1/_3$ to $^1/_{10}$ are common.

5. The plate-grid capacitance is much lower and the plate-ground capacitance is somewhat higher in pentodes than in comparable triodes.

Space-Charge-Grid Pentodes

One limitation in the 3-electrode tube and in the multielectrode tubes considered thus far in this paper, is the resistance offered by space charge to the flow of space current. Tubes having so-called space-charge grids overcome this limitation to some extent by having a positive grid close to the cathode, which partially neutralizes the negative field very near the cathode surface due to space charge. A comparatively large current is drawn from the cathode by the space-charge grid. A portion of this current (usually about half of it) is collected by this grid, while the remaining portion passes through it and is acted on by the remaining elements of the tube.

The arrangement of the electrodes in a space-charge-grid pentode is shown in Fig. 13. The space-charge grid, $g1$, is maintained at a relatively low positive potential with respect to the cathode, usually in the range from 10 to 20 volts. The second grid, $g2$, is the control grid and is maintained at a negative potential with respect to the cathode.

Ideally, at some cylindrical surface between these 2

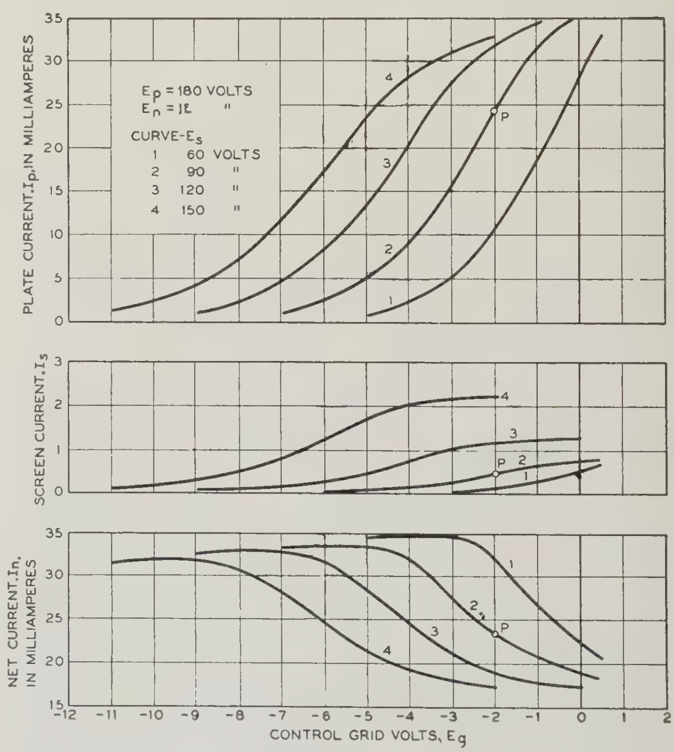


Fig. 15. Characteristics of a space-charge-grid pentode

Plate current, screen current, and net current as functions of the control-grid voltage, E_g, with the indicated values of screen voltage as parameters. Plate voltage, E_p = 180 volts. Net voltage, E_n = 15 volts

grids (assuming the structure to be cylindrical) the electrons are retarded to nearly zero velocity forming a second space-charge region which may be regarded as a virtual cathode. Since this space-charge sheath is larger in area than the original cathode and is very close to the control grid, it results in very large values of transconductance. Practically, the ideal condition is not fully realized, largely because velocity components other than radial are imparted to the electrons in passing through the space-charge grid. Consequently, these electrons reach any given cylindrical surface outside the space-charge grid with rather widely varying radial components of velocity. This, as will be seen later, places a rather serious limitation on the performance of such tubes.

The arrangement and functioning of the other electrodes in Fig. 13, outward from the virtual cathode, corresponds with that of the screen grid tetrode. The screen grid, $g3$, is maintained at a fixed positive potential necessary to accelerate the electrons from the region of the virtual cathode. The plate must be maintained at a potential higher than that of the screen for the same reason as in the screen grid tetrode. It will be shown that the characteristics of this pentode correspond roughly with those of the screen grid tube previously discussed.

If $g3$ were omitted, the structure outside the virtual cathode would correspond to that of a triode and the characteristics in the resulting tetrode would correspond roughly to those of a triode. In Fig. 14, characteristics are shown for a pentode of this type, the cathode and general dimensions of which are the same as those of the power pentode, the characteristics of which were shown previously. The plate current and screen current curves are seen to correspond very closely with those previously shown for a screen grid tube. The characteristics exhibit the same "folds" due to secondary electrons, although this portion of the characteristics is not shown. The net or space-charge-grid current I_n increases as the plate current decreases with increasing negative control grid voltage. This is to be expected since, as the control grid becomes more negative and reduces the current passing through it to the plate, the excess current returns to the net rather than to the cathode as in the screen grid tube.

If values of the amplification factor, plate resistance, and transconductance are plotted as functions of the plate voltage, families of curves are obtained similar in all respects to those for a screen grid tube as shown in Figs. 3 and 5. These characteristics are not shown for this tube.

In Fig. 15, plate current, screen current, and net current characteristics are shown as functions of the control grid voltage with different values of the screen voltage as parameters. As in the case of the screen grid tube, only a slight displacement of the characteristics results from variation of the plate voltage. It is of interest to note the high values of net current, particularly as the plate current drops toward zero with increasing negative grid bias. For example, if the operating point is chosen at P in Fig. 15, with a screen potential of 90 volts and a grid potential of -2 volts, the plate current, screen current, and net current are 24, 0.5, and 23 ma,

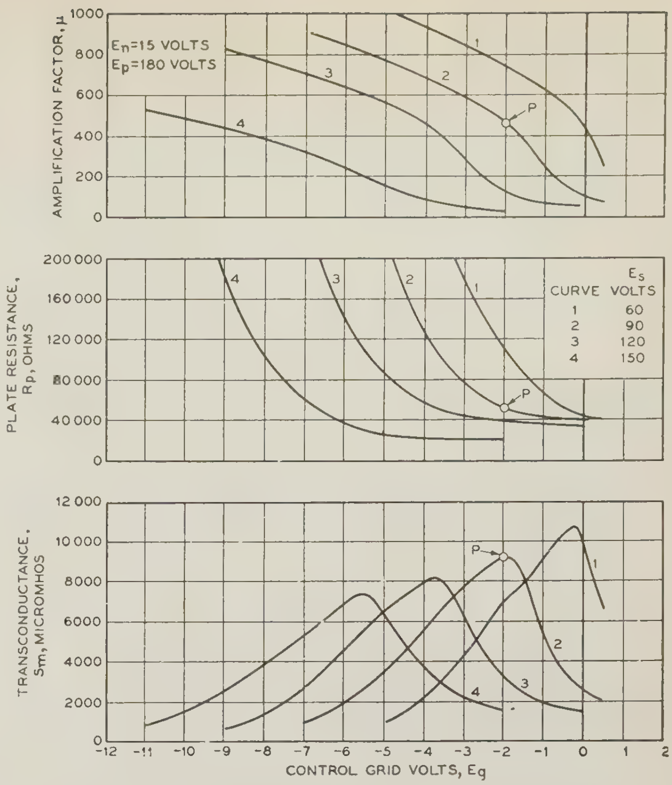


Fig. 16. Amplification factor, plate resistance, and transconductance of a space-charge-grid pentode as functions of the control-grid voltage

respectively, making a total space current of 47.5 ma drawn from the cathode, nearly half of which is collected by the space charge grid.

Another point of interest in Fig. 15 is the flattening out of the plate current characteristics at the higher values of plate current, in a manner very similar to that exhibited by triodes of low cathode emission. In fact, this phenomenon is caused by the partial exhaustion of the space charge in the region of the virtual cathode. This is a fundamental characteristic of space-charge-grid tubes, caused largely by the imperfect character of the virtual cathode, which results from electrons entering the space charge region with widely varying normal components of velocity. It constitutes a serious limitation on the practicable range of operation of such tubes, since it prevents the plate potential from swinging over a sufficiently large range to obtain a large power output without resulting in prohibitive distortion.

In Fig. 16, the amplification factor, plate resistance, and transconductance are shown as functions of control grid voltage, with the same parameters as were used in obtaining the curves of Fig. 15. Of particular interest in these curves, are the unusually high values of transconductance for a tube of this size. For example, at the selected operating point P it is 9,200 micromhos. Also of interest is the peaked character of the transconductance curves. Since transconductance is defined by the slope of the plate current-grid voltage curves, which for this tube have points of inflection in them, maximum points must occur in the transconductance curves. The rapid falling off in transconductance on either side of the maxima, with change in grid voltage, also in-

dicates that a large amount of distortion would result if the tubes were operated with large swings in grid potential.

Space-charge-grid pentodes are capable, then, of yielding very high amplification because of their extraordinarily high transconductance; but, practically, they are limited to use as voltage amplifiers for fairly small inputs, since operation over the wide range necessary for large power output results in prohibitive distortion. These statements apply also to space-charge-grid tetrodes. These tubes have the advantage over ordinary triodes, however, of yielding high values of transconductance at comparatively low voltages applied to the plate.

Dielectric Properties of Cellulose Paper—II

Studies of the dielectric properties of pure cellulose paper as related to its moisture content were reported in Part I of this paper, which was published in the October issue. In Part II, presented herewith, the variations in dielectric properties as related to temperature are discussed. These investigations not only throw additional light on the theoretical aspects of dielectric absorption, but also reveal information of practical importance to cable manufacturers.

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IN PART I of this paper, studies of the electrical properties of cellulose paper as related to the moisture content have been reported. In Part II, presented herewith, these studies have been extended to the variation of the electrical properties as related to temperature when the paper is in a state of extreme dryness. These matters are of interest because the electrical properties of the paper during the vacuum drying process are used by manufacturers for determining the proper condition for impregnation, and further, because it has been shown[1] that the properties of the paper before impregnation constitute an important factor in the final behavior of cable insulation of the best type.

Further grounds for interest are the additional light thrown on the uncertain question of the nature of dielectric absorption and dielectric loss in dry paper and the fact that no satisfactory explanation has been offered for observed increases with temperature of the apparent dielectric constant of cable insulation both before and after impregnation.

In the portion of the investigation reported in this part of the paper, samples of dry kraft cable paper were studied over the temperature range from 20 to 100 deg C. At each temperature the dielectric properties were measured for both alternating and continuous stresses and the results used for an analysis of the measured values. The chief conclusions are:

1. Power factor and capacitance as measured under alternating stress may be predicted accurately from short-time charge and discharge curves under continuous stress.

2. Reversible absorption is found to account for the whole of the measured power factor from 20 to 70 deg C; from 70 deg C the component due to irreversible conduction becomes appreciable.

3. Over the whole range of temperature studied, the component of capacitance attributable to reversible dielectric absorption is found to be approximately equal to the difference between the apparent capacitance and the geometric capacitance.

4. A large increase in measured capacitance observed between 20 and 100 deg C has been found to be caused principally by a concurrent increase in geometric capacitance occasioned by thermal expansion of the electrode system.

5. A separate study of the change in the dimensions of the electrode system has permitted derivation of the variations with temperature of the true capacitance and dielectric constant.

6. Over the range from 20 to 100 deg C there is little change in the measured dielectric constant or in the geometric dielectric constant of dry paper. Within the upper range of temperature, there is a slight falling off in these values which is attributed to a decrease of density caused by thermal expansion of the dielectric.

Specimen and Measurements

Test Sample. A photograph of the experimental sample is reproduced in Fig. 15. Dimensions and other details of the sample, together with those of the drying tanks, and pumping and temperature control equipment, have been given in foregoing papers.[1, 2, 3] For measuring the temperature of the sample, 2 carefully calibrated resistance thermometers were used, one fitting closely inside the brass cylinder electrode, the other mounted immediately adjacent to the outer lead electrode. The whole assembly was enclosed within a vacuum tank equipped with close temperature control. By these arrangements, the temperature of the insulation could be determined within 0.1 deg C.

Part II of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted July 12, 1934; released for publication Aug. 24, 1934. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

Experimental Procedure. The sample was dried at 105 deg C and under vacuum of 0.25 mm (of mercury) until the final conductivity, as measured at a continuous potential of 1,500 volts had reached the low constant value of 3×10^{-16} mho per cm.[3] The tank then was filled with well dried air at atmospheric pressure and sealed off. From power factor measurements, and by the method described in Part I of this paper, the sample then had a moisture content of approximately 0.08 per cent of its total volume.

In this condition, the following measurements were made:

1. Capacitance-frequency from 60 to 20,000 cycles.
2. Power factor, capacitance, and loss at 60 cycles and 500, 1,000, and 1,500 volts, respectively.
3. Short-time measurements (amplifier oscillograph) of charge and discharge currents at a continuous potential of 1,500 volts for the time interval 0.001 to 0.030 sec.
4. Long-time measurements of charge and discharge currents at a continuous potential of 1,500 volts, extending to 40 min.

These measurements were made in the order given, at each of 6 different temperatures from 100 to 20 deg C, the order being from higher to lower temperatures. Normally 2 complete sets of measurements were made at each temperature and their average taken. A period of 24 hr or more was allowed between each successive pair of temperatures to insure equilibrium conditions.

Experimental Results

Capacitance and Power Factor at 60 Cycles. In Fig. 16 is shown the observed 60-cycle power factor and capacitance as functions of the temperature. The power factor exhibits the conventional minimum at about 70 deg C, with rise thereafter commonly attributed to increase in conduction.

The capacitance increases from 752 $\mu\mu$f at 23 deg to 787 $\mu\mu$f at 100 deg C, an over-all increase of about 5 per cent. This type of increase has been noted in earlier papers and also by cable manufacturers, but never has been completely understood. It now is explained for the first time, the authors believe, by measurements reported in this paper.

Frequency-Capacitance. Measurements of capacitance as related to frequency up to 20,000 cycles are shown in Fig. 17. These curves show the well-known decrease of capacitance with frequency resulting from the diminishing effect of dielectric absorption with increasing frequency. The decrease is more rapid at high than at low temperatures, but the magnitude of the total change is greater at the lower temperatures. In all cases the capacitance in the regions of higher frequency, where it is apparently constant over a wide range, is assumed to be the true geometric capacitance of the paper sample. Note that the geometric capacitance so measured, as well as the 60-cycle capacitance, increases with increasing temperature—an unexpected result.

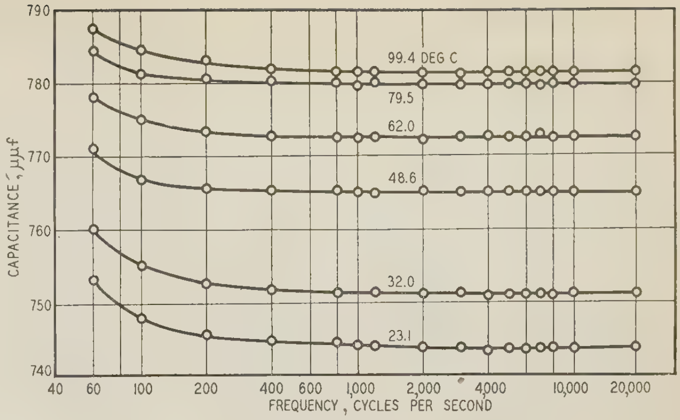

Fig. 17. Variation of capacitance with frequency at different temperatures

D-C Measurements. The discharge curves plotted from the amplifier oscillograph records are shown in Fig. 18. Below 70 deg C no difference between the charge and discharge curves could be detected, indicating the absence of measurable conduction. No great difference in the shapes or positions of these curves below 60 deg C is evident. Above 60 deg C, the well-known tendency to a steep initial portion and a higher final portion with increasing temperature begins to be evident. Using the von Schweidler method of computation, as extended by Whitehead and Banos,[4] these short-time curves may be used for computing the separate components of the dielectric loss due to dielectric absorption and to conduction, and also the component of capacitance due to absorption. An example of the photographic record has been given in Fig. 6 of Part I of this paper.

The results of the long-time d-c measurements are given in Table III. At low temperatures the 40-min charge and discharge currents at 1,500 volts can scarcely be detected and are extremely small at

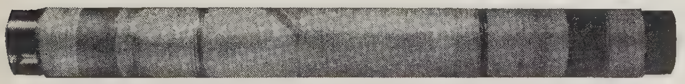

Fig. 15 (above). Completed paper sample

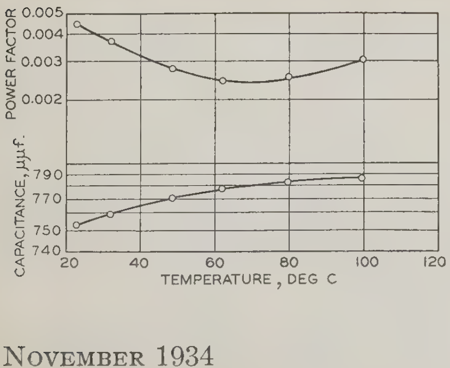

Fig. 16 (left). Variation of apparent power factor and capacitance with temperature

Table III—Results of Long-Time D-C Measurements

Temperature, Degrees C	1,500-Volt Charge Current at 40 Min, Amperes	1,500-Volt Discharge Current at 40 Min, Amperes
23.5	0.05×10^{-10}	
32.8	0.09×10^{-10}	0.07×10^{-10}
48.4	0.5×10^{-10}	0.5×10^{-10}
62.6	1.7×10^{-10}	1.0×10^{-10}
79.0	117×10^{-10}	46×10^{-10}
99.3	650×10^{-10}	125×10^{-10}

Table IV—Analysis of Power Factor and Capacitance of Paper Samples Versus Temperature

1	2	3	4	5	6	7	8	9
	Power Factor				Capacitance, $\mu\mu f$			
		D-C Short-Time Analysis						
Temperature, Deg C	60-Cycle Bridge Measurement	Absorption	Conduction	Abs. + Cond.	60-Cycle Bridge Measurement C	Geometric Capacitance (∞ frequency) C_∞	Absorption Capacitance $C - C_\infty$ or $\triangle Cr$	D-C Analysis, Absorption Capacitance $\triangle Cr$
23.5	0.004408	0.00442		0.00442	752.7	743.5	9.2	8.82
32.8	0.003693	0.00369		0.00369	759.6	751.8	7.8	8.02
48.4	0.00276	0.00274		0.00274	770.3	764.8	5.5	5.06
62.6	0.002418	0.00242		0.00242	777.3	772.8	4.5	4.27
79.0	0.002512	0.00243	0.00007	0.002503	783.9	779.3	4.6	4.15
99.3	0.003127	0.00296	0.000215	0.00316	786.5	781.3	5.2	4.7

63 deg C. No appreciable difference was found between them. For higher temperatures, however, both charge and discharge currents are greater, the former increasing more rapidly with temperature so that the difference, which is the conduction current, is correspondingly greater. Briefly, this means that the leakage conduction is negligibly small at low temperatures, but becomes appreciable at higher temperatures.

Variation of Capacitance and Power Factor With Voltage. At a-c potentials of from 500 to 1,500 volts (8 to 25 volts per mil), 60 cycles, both power factor and capacitance were constant at each value of temperature.

Discussion of Results

A-C D-C Correlation. Table IV, which contains a summary of the experimental results, indicates the excellent agreement between the measured values of power factor and those computed from the d-c measurements of absorption and conduction. A similar agreement is found between the 60-cycle capacitance and the capacitance computed from the geometric value and the component due to absorption as computed from the d-c observations. Column 6, giving the sums of the computed power factor components of absorption and conduction is to be compared with column 2, the measured values of power factor. Column 8 gives the differences between the apparent capacitances at 60 cycles and the geometric capacitances. Column 8 agrees quite closely with column 9 in which is given the component of capacitance attributable to absorption, as computed from the d-c discharge curves.

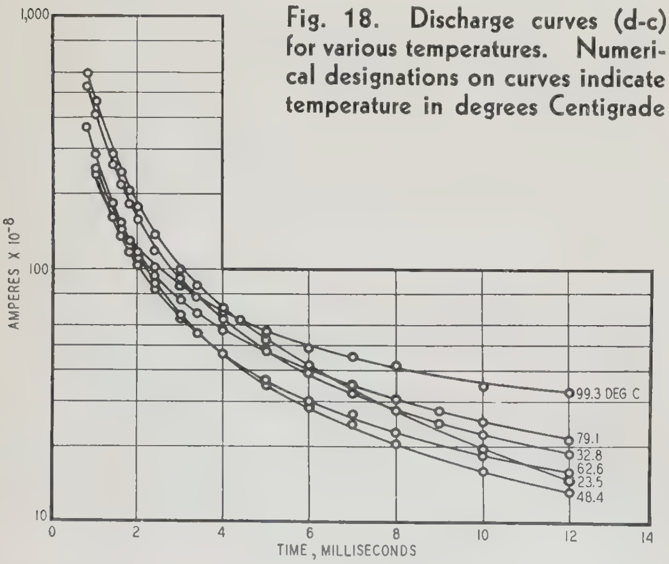

Fig. 18. Discharge curves (d-c) for various temperatures. Numerical designations on curves indicate temperature in degrees Centigrade

Analysis of Power Factor. Variation of the separate components of the power factor with temperature is shown in Fig. 19. The upper curve is the measured or apparent power factor and the next lower curve is the power factor component attributable to absorption. The lowest curve is the component due to conduction and its ordinates are equal to the difference between the ordinates of the 2 upper curves. As already noted, the conduction component is absent below 70 deg C, showing that in the dielectric loss below this temperature the

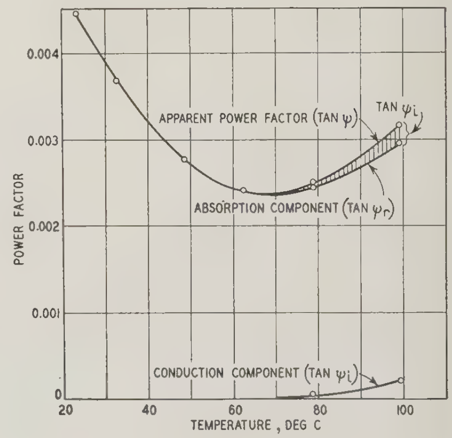

Fig. 19. Analysis of power factor

leakage conduction is negligible compared with the effect of dielectric absorption. Above 70 deg C, conduction becomes appreciable and increasingly so with further rise of temperature. The rise in this familiar type of curve, beyond the minimum value, commonly has been attributed entirely to increasing conduction. It is of interest, therefore, to note that in dry paper a substantial and in fact the greater part of this rise is due to absorption, certainly in the earlier stages. A qualitative explanation of this may be found in Wagner's 2-layer development of Maxwell's theory of absorption, by assuming suitable shapes of the conductivity temperature curves of the constituent dielectrics.[5]

Analysis of Capacitance. Variation of the apparent capacitance and that of the geometric capacitance with temperature is shown in Fig. 20. The difference between these 2 curves is the component of capacitance attributable to dielectric absorption which may be computed from the d-c measurements; the values so computed agree closely with the differences between curves 1 and 2 in Fig. 20, as shown in Table IV. These differences are plotted in Fig. 21; the component of capacitance due to absorption is seen to pass through a minimum at about the same temperature at which a similar minimum of power factor was observed.

The increase in the geometric capacitance with temperature, as shown in Figs. 17 and 20, was quite unexpected, and it immediately suggests an obvious explanation of the heretofore unexplained increase with temperature in the measured values of capacitance both in laboratory samples and in cables as manufactured. It is well known that under certain conditions, increasing temperature may cause an increase of capacitance due to dielectric absorption, and elsewhere this has been suggested as a possible cause of the temperature increase of capacitance of impregnated insulation. The geometric capacitance, however, should show either a constant value with increasing temperature, or a very slow decrease due to a change in density. It is suggested immediately, therefore, that these large changes must be caused by changes in the dimensions of the sample due to thermal expansion. This is found to be the correct explanation, proceeding as follows:

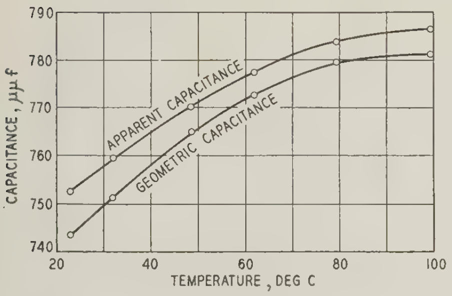

Fig. 20. Variation of components of capacitance with temperature

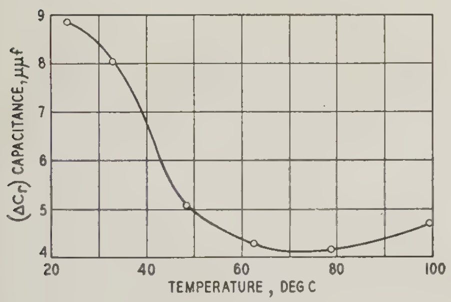

Fig. 21. Variation of absorption component of capacitance with temperature

Let

C_a = the electrode system capacitance (in vacuum and with no dielectric)

ΔC_a = the increase in electrode system capacitance due to temperature expansion

C_∞ = the geometric capacitance of the composite paper sample

ΔC_∞ = the increase in geometric capacitance of the paper sample corresponding to the temperature increase

$$C_a = K\frac{0.2416\,l}{\log_{10}\frac{b}{a}} = \frac{6.17}{\log_{10}\frac{b}{a}}$$

The point on the curve indicated by a cross (⊗) indicates the values for the test specimens used in these studies; at that point C_a = 311.7 μμf at 25 deg C; b = 2.61567 in.; a = 2.5 in.; b/a = 1.0467

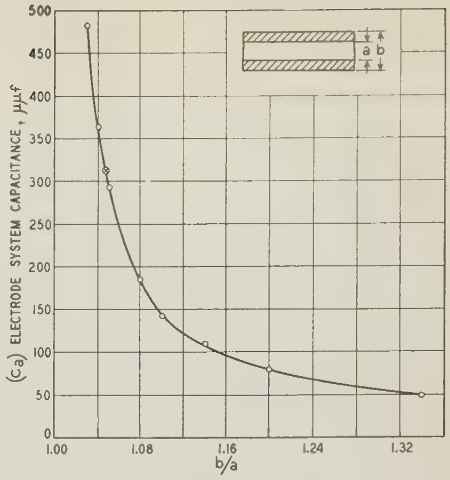

Fig. 22. Capacitance of electrode system as a function of the ratio of outer and inner electrode diameters

K_∞ = the geometric dielectric constant of the paper sample

Then

$$C_aK_\infty = C_\infty \tag{1}$$

and further

$$(\Delta C_a + C_a)\,K_\infty = C_\infty + \Delta C_\infty \tag{2}$$

Hence

$$\Delta C_\infty = K_\infty \cdot \Delta C_a \tag{3}$$

Equation 3 indicates that any increase due to temperature in the geometric capacitance of the sample, divided by the geometric dielectric constant of the dielectric gives the change in the capacitance of the electrode system that must take place if this change is to account for the increase in the measured values. Since the geometric dielectric constant of paper is approximately 2.5, a change of 4 μμf for example, in the value of C_a is sufficient to account for a change of 10 μμf in the value of C_∞. In other words, a relatively small change in the electrode dimensions is reflected in a larger over-all change in geometric capacitance due to the dielectric constant.

In the foregoing studies, test samples always have been enclosed in constant temperature vacuum tanks and accurate measurements of changes in dimensions resulting from changes in temperature were not possible. In view of the foregoing, however, it becomes important to make an accurate study of these changes.

Expansion of Test Sample With Temperature

Dimensions of Sample. The inner cylinder of Fig. 15 forming the high voltage electrode is of brass having inside and outside diameters of 2.2 in. (5.6 cm) and 2.5 in. (6.35 cm), respectively, giving a section of 0.15 in. (0.38 cm). Fifteen layers of paper form a wall of about 0.06 in. (0.152 cm). Over this is the close fitting lead sheath forming the measuring electrode. This sheath has a longitudinal slot about 6.3 mm wide to allow for temperature expansion (a thin strip of lead foil under this slot closes it electrically). The sheath is held in place by

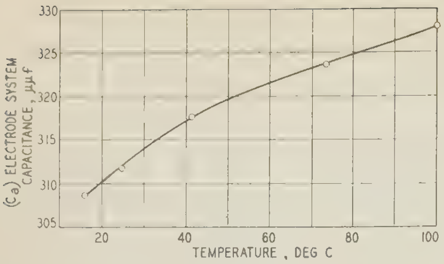

Fig. 23. Variation of electrode system capacitance with temperature as computed from observed changes in electrode diameters

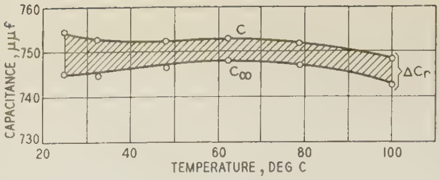

Fig. 24. Capacitance as a function of temperature, corrected for electrode expansion

C = Apparent capacitance
C_∞ = Geometric capacitance
ΔC_r = Absorption component of capacitance

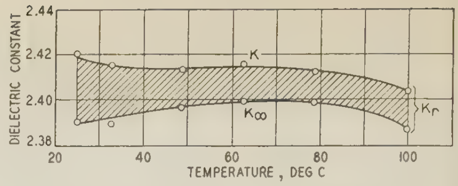

Fig. 25. Dielectric constant as a function of temperature

K = Apparent dielectric constant
K_∞ = Geometric dielectric constant
K_r = Absorption component of dielectric constant

a single layer of linen thread wound at a tension of about 15 lb.

Of these concentric elements, the lead has the highest coefficient of thermal expansion, while that of the thread is very small. Almost equally as small is the expansion coefficient of the paper in a radial direction. The expansion coefficient of the brass cylinder, although not so great as that of the lead, is still considerably greater than that of the dry paper. Bearing these things in mind it is noted that the diameter of the inner cylinder increases linearly with temperature. The lead electrode experiences a considerable circumferential expansion; but because of the negligible expansion of the binding layer of thread, the net result is that with increasing temperature, the slot in the lead sheath closes up and the over-all diameter of the sample remains practically the same. The paper insulation thus is caught between an expanding inner cylinder and a nonexpanding outer cylinder, and necessarily suffers a contraction of wall thickness approximately determined by the increase in diameter of the inner electrode. In this picture a slight volumetric expansion of the paper itself has been neglected; this seems a not too inaccurate assumption in view of the low thermal coefficient of expansion of the paper. It remains to be seen whether this picture is sufficient to account for the observations.

In Fig. 22 are plotted as ordinates values of capacitance of a cylindrical capacitor and as abscissas the ratio, b/a, of the outer to the inner diameters. The point on the curve marked with a cross indicates the corresponding values for the test specimen used in these studies. It may be seen that this point is in a region where a relatively small change in the value of b/a is accompanied by a very large change in the value of capacitance. As a matter of fact, simple computation using the formula shown in the figure indicates that an increase in the diameter of the inner cylinder of about 0.2 per cent without corresponding increase in the diameter of the outer cylinder will completely account for the 5-per cent increase in geometric capacitance observed between 25 and 100 deg C. Moreover, using an average value for the coefficient of expansion for brass, as taken from technical literature, an increase of the diameter of the cylinder of about 0.2 per cent was to be expected over the temperature range studied. Therefore, the large increase in geometric capacitance of the sample apparently is explained on the basis of an increase of electrode diameter. It remains only to check these assumptions and the conclusions by direct measurement.

It should be noted that the longitudinal expansion of the lead electrode also will cause an increase in the geometric capacitance of the electrode system. This increase, however, is relatively small compared with that resulting from the change in diameter, as will be seen later.

Measurement of Thermal Expansion. A sample was cut in 2 parts at the center so as to expose a clean circular cross section, and was mounted in a thermostatically controlled constant temperature box having a large glass observation window. The sample was suspended from the roof of the box by a pendulum type of support in order to minimize local vibration. Thermometers placed at intervals about the sample and in contact with it, were used to obtain the average temperature. A high power microscope fitted with a micrometer head reading to 0.0001 mm was mounted as cathetometer immediately outside the observation window, and could be focused on any point of a diameter of the cross section of the sample.

The temperature of the sample was set at 5 values between 16 and 100 deg C. At each temperature, the shifts from a fixed zero along a fixed diameter, of the surfaces of separation between brass and paper and paper and lead were measured accurately for both ascending and descending temperatures and along 2 different diameters of the specimen. The results of these 4 sets of measurements then were averaged to give the final results which appear in Table V. It may be noted that the column marked "b" indicates no change in the inside diameter of the lead sheath, and column "a" indicates a progressive increase in the outer diameter of the brass cylinder. The succeeding columns show the progressive decrease in the ratio b/a, and the last column shows the corresponding increases in the geometric capacitance of the electrode system. During these observations, the expansion and contraction in the longitudinal slot in the outer electrode were easily seen.

Values given in the last column of Table V have been plotted as related to temperature in Fig. 23, which thus shows the increase in capacitance resulting from diametral expansion. A small increase resulting from longitudinal expansion of the lead sheath is included in this curve although its contribution to the total change is very small. Comparison

Table V—Thermal Expansion of Component Parts of the Paper Specimen

Avg Temp, Deg C	A Mm	B Mm	h Mm	ΔA Increase in A From 25°C Value, In.	a In.	b In.	b/a	log b/a	C_a $\mu\mu$f
16.2	0.4640	1.9470	1.4830	−0.00055	2.4989	2.61567	1.04673	0.019837	308.66
25.0	0.4780	1.9470	1.4690		2.5000	2.61567	1.04627	0.019643	311.7
41.8	0.5043	1.9470	1.4427	+0.001035	2.50207	2.61567	1.045403	0.0192853	317.17
73.5	0.5309	1.9471	1.4162	0.002085	2.50417	2.61568	1.044524	0.0189202	323.33
100.3	0.5466	1.9471	1.4005	0.002701	2.5054	2.61568	1.0440	0.018700	327.5

A = } Expansion shifts along a diameter of brass and lead
B = } edge, respectively, from a fixed arbitrary zero
$h = A\text{-}B$
a and b are as shown on Fig. 22

At 25 deg C $a = 2.5000$ in., $b = 2.61567$ in. } measured with micrometer calipers (averaged values)

$a_t = 2.5000 + 2\ \Delta A$ (at temperature "t")

$C_a = \dfrac{6.1729}{\log_{10} b/a_t}$ (at temperature "t")*

* Assuming test electrode length to remain constant. Longitudinal thermal expansion of the lead sheath causes an additional increase in electrode system capacitance, C_a, amounting to a total of 0.66 $\mu\mu$f which is about 4 per cent of the increase resulting from radial expansion from 25 to 100 deg C. The curve of C_a in Fig. 23 and the curves in Figs. 24 and 25, however, include the effects of both radial and longitudinal expansion.

of Fig. 23 with Fig. 20 indicates at once that the greater part of the temperature variation shown in the latter may be accounted for by thermal expansion. If the values given in Fig. 20 be corrected for change of electrode capacitance by the values given in Fig. 23 the values shown in Fig. 24 are obtained. Noting the extended scale on which the capacitance is plotted in Fig. 24, it may be seen that when corrected, the changes indicated for both geometric capacitance and apparent or measured capacitance over the entire temperature range are exceedingly small.

The same conclusion may be expressed in terms of dielectric constants. If the observed geometric capacitance at each temperature be divided by the corresponding capacitance of the electrode system as given in Fig. 23, a value is obtained that may be called the geometric dielectric constant of the paper. The result is shown in Fig. 25 which also contains a similar corrected curve for the apparent dielectric constant as measured at 60 cycles. Again the overall changes in the dielectric constants, both geometric and total, of the paper itself are very small over the temperature range studied.

Although as indicated, the total changes in the values of dielectric constant and over-all capacitance are not great, they nevertheless are of apparently definite character. The measurement of capacitance was very accurate and there seems to be no reason to question the actuality of the changes indicated in the curves of Figs. 24 and 25. It may be seen that at first the geometric dielectric constant increases with temperature up to about 70 deg C and thereafter decreases. Nothing definite can be said as to the causes of these variations, but the following is suggested: In the lower range, compression of the paper results in an exclusion of air and a consequently greater ratio of fiber to air, that is, an increase in density greater than the decrease resulting from the change in temperature. Beyond a certain point, however, this effect must cease and the longitudinal thermal expansion of the paper wall thereafter causes a decrease in density giving the descending portion of the curve in the higher range of temperature. This latter type of variation with temperature from the cause suggested is well known for liquid and plastic materials.

With reference to the initial descending portion of the curve for K, the over-all measured dielectric constant, from Fig. 21 the rapidly descending value of the component of capacitance due to dielectric absorption within the range 30 to 60 deg C may be noted. This is reflected in the curve of Fig. 25. The further tendency to lower values in the upper range of temperature may be accounted for on the same grounds as proposed for the geometric dielectric constant, namely, decreasing density resulting from longitudinal expansion. In Part I of this paper were reviewed briefly the suggestions that have been made for the mechanism of dielectric absorption as resulting from residual moisture, and as accounting qualitatively for the observed behavior of power factor and capacitance.

As a general result of the foregoing, it should be noted that in the use of cylindrical condensers for the study of dielectrics over any considerable temperature range, large errors in measured and computed values may arise from thermal expansion of the electrode system. These errors are greater the smaller the ratio of diameters of outer to inner electrodes. Although no measurements of the magnitudes of these temperature changes have been made on impregnated samples, temperature variations of measured capacitance have been found for such samples and a similar variation frequently has been noted in the capacitance measurements on high voltage cables. It appears highly probable from the results here reported that within the range from 20 to 100 deg C the dielectric constant of impregnated paper insulation undergoes little if any change, and further, that the increases of capacitance with temperature frequently noted in both cables and laboratory samples are caused by corresponding temperature changes in the dimensions of the electrode systems.

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Vacuum Tubes as High Frequency Oscillators

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Vacuum tubes as oscillators and amplifiers at frequencies greater than 100 megacycles (3 m) are considered in this paper. The type of construction used in a large number of different tubes, and the characteristics of the tubes, are presented. Circuits for operating the tubes also are considered and the theory of operation and the factors limiting ultra-high frequencies are discussed. Principal attention is given to the tubes as oscillators, with brief consideration of the problem of amplification.

THE 3 types of oscillation generators which at present are the most efficient in the range from 100 megacycles to 3,000 megacycles per second will be discussed in the following survey. These are: the negative grid tube which at lower frequencies is the conventional regenerative oscillator, the positive grid or Barkhausen oscillator, and the "magnetron" oscillator. The amplification problem will be briefly discussed. Because of the present unsettled state of the theory, only the most elementary and generally accepted part will be included. Much theoretical and experimental work remains to be done before knowledge of the mechanism of oscillation and amplification in this frequency range will be satisfactory. As is often the case, the empirical knowledge of some of these mechanisms has outdistanced the theoretical interpretation.

The Negative Grid Oscillator

The conventional thermionic vacuum triode, whether it be a large water cooled power tube or a small receiving tube, may be used as a generator of oscillations varying in frequency from a few cycles per second to some 20 or 30 megacycles with substantially undiminished efficiency and output. In this range the frequency at which a tube is to be employed is a factor of almost negligible importance in the determination of its characteristics and its form. Beyond this range, however, frequency plays an increasingly important part, and as one approaches 300 megacycles, it becomes the most important factor in the determination of tube design.

When an attempt is made to operate a standard triode at increasingly high frequencies it is found that the output and efficiency begin to decrease. The frequency at which this is first observed will depend upon the design of the tube but it will usually be in the 10 to 60 megacycle range. By successive modifications of the circuit arrangement and size this decrease in power output and efficiency can be minimized. With optimum circuit arrangements, however, this decrease continues until finally a frequency is reached beyond which oscillations can no longer be produced.

In Fig. 1 are shown typical data for a standard 75-watt tube, the Western Electric type 242*A*, operated with reduced potentials over the frequency range from the point where oscillation frequency noticeably affects performance to the point where oscillations can no longer be produced. The plate potential was held constant at 750 volts throughout the entire frequency range. The oscillation circuit was modified at each point in order to obtain maximum output and efficiency, keeping the anode dissipation within the maximum rating of 100 watts and the anode current within the maximum rating of 0.150 amp. It can be seen from the curves that the output and efficiency are independent of the frequency until about 20 megacycles is reached, when they begin to decrease. At 100 megacycles the output power is only 2.5 watts and the efficiency only 2 per cent. The tube will not oscillate at 105 megacycles.

Effect of Energy Losses on Performance

A tube operating in the range where frequency affects performance must withstand energy losses, and the resulting heating within its structure, which occur to only a negligible degree at the lower frequencies. Some of these losses are due to dielectric hysteresis in the insulating materials of the tube, particularly in the portions of the glass supporting stem or bulb which lies between the tube leads. The

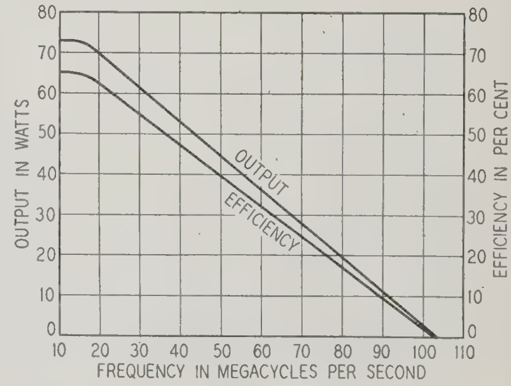

Fig. 1. Power output and anode efficiency as a function of frequency for a standard triode

These curves are typical of all tubes as they approach their upper limiting frequency

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glass is sometimes so softened by the heat thus developed that it is punctured by the outside air pressure. Losses also occur in the auxiliary metallic parts of the tube structure due to the increased eddy currents that occur at high frequencies. Losses in the tube electrodes and their lead-in wires are also greatly increased due to skin effect which increases their resistance, and due to the increased charging current required by the interelectrode capacities. The increased lead temperature, depending upon its amount, will cause a more or less rapid deterioration of the lead-to-glass seals which may ultimately destroy the vacuum. In order to protect the tube from damage because of these new types of energy dissipation, the operating potentials and currents must be reduced to values less than those established for low frequency operation. Some manufacturers are now giving special ratings on such of their standard tubes as may be used at ultra-high frequencies. These ratings should be adhered to when operating in this range.

Effect of Circuit on Performance

The decrease in output power and plate efficiency which sets in with the increase in frequency, while due in part to the losses described above, and to the rapid increase in radiation losses, is also due to 2 additional effects of fundamental importance. The first to become evident, with increasing frequencies, is circuital in nature. This can be explained by reference to the conventional oscillator shown in Fig. 2. The frequency of such an oscillator is given by

$$f = \frac{1}{2\pi\sqrt{LC}},$$

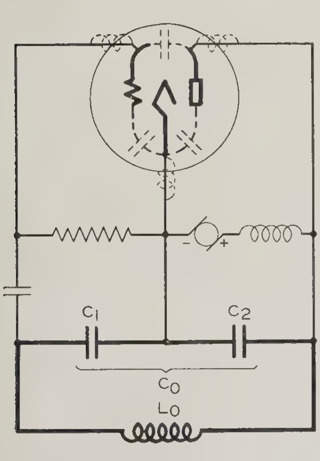


Fig. 2 (left). A standard Colpitts oscillator circuit

The heavy lines indicate the main oscillating circuit. The dotted portions represent the interelectrode capacities and lead inductances which play a minor rôle at low frequencies

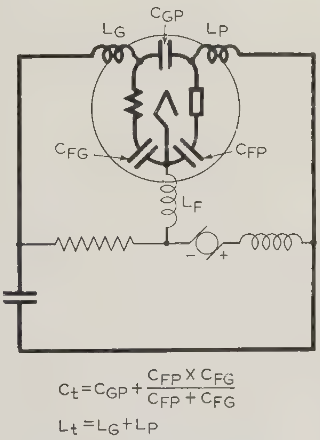


Fig. 3 (right). The limiting circuit with the external tuning capacity eliminated and the external inductance reduced to a short circuiting bar between the grid and plate leads

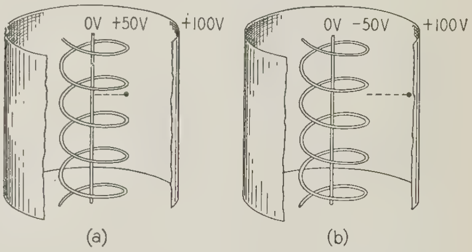
The main oscillating circuit, indicated by the heavy lines, is seen to include the interelectrode capacities and lead inductances

where L and C are the effective inductance and capacity of the oscillating circuit. In the lower frequency range, the LC product which determines the frequency is substantially equal to L_0C_0, that is, to the product of the inductance and capacity of the external circuit. The inductance of the tube leads and the capacity between its electrodes (indicated by the dotted lines in the figure) play a negligible rôle. In order to tune the circuit to higher and higher frequencies, the capacity C_0 is first reduced and finally eliminated, leaving the interelectrode capacity as the only capacity in the oscillating circuit. The tube leads then form a part of the main oscillating circuit, in which large circulating currents must exist for stable operation. For a further increase in frequency the external inductance L_0 must be reduced and, in the limit, it becomes the shortest possible connection between the grid and plate terminals. The oscillating frequency for this limiting circuit, shown in Fig. 3, is determined by the product of the lead inductance L_t and the interelectrode capacity C_t; that is,

$$f_0 = \frac{1}{2\pi\sqrt{L_tC_t}},$$

where L_t is the sum of the grid and plate lead inductance and C_t is the total grid-plate capacity. Even before this frequency limit is reached the output power and plate efficiency are seriously reduced by the lack of full control over the relative amplitude and phase of the alternating grid and plate potentials. Whereas the ratio of these amplitudes is controlled in the circuit shown in Fig. 2 by the condensers C_1 and C_2, it is determined in the limiting case primarily by the fixed ratio of the grid-filament to plate-filament interelectrode capacities. Most tubes made especially for ultra-high-frequency use are constructed so as to minimize these circuit limitations by a reduction in the interelectrode capacity and lead inductance and by adjusting the capacity ratio.

Fig. 4. Illustrating the mechanism which enables electrons to take energy from the oscillating circuit



Effect of Transit Time on Performance

The second fundamental effect has to do with the time required for the electrons to travel from the cathode to the anode within the tube structure. This time, the so-called transit time, is very small in present-day commercial types of power tubes, usually much less than one microsecond. Obviously at low frequencies it can be neglected and, in fact, for many tubes it still plays a minor rôle either in determining the output and efficiency in the high

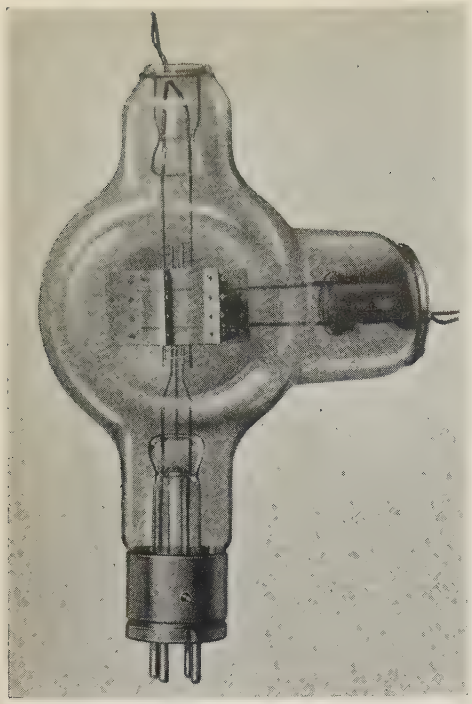


Fig. 5. A radiation cooled tube for use in the frequency range from 60 to 180 megacycles per second

Note the large ratio of the plate diameter to plate length and the special arrangement of the leads

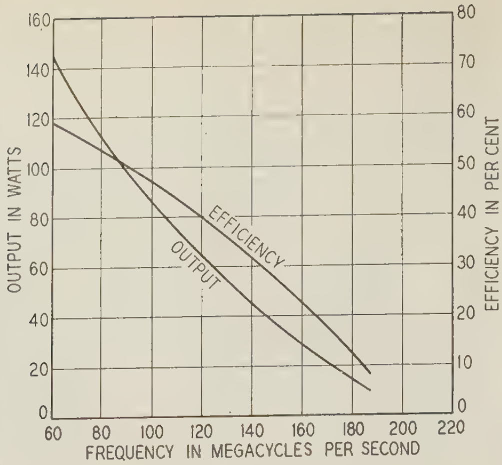


Fig. 6. Output and efficiency as a function of frequency for the tube shown in Fig. 5

A comparison of these curves with those shown in Fig. 1 illustrates the improvement obtained by taking account of those factors which become important at high frequencies

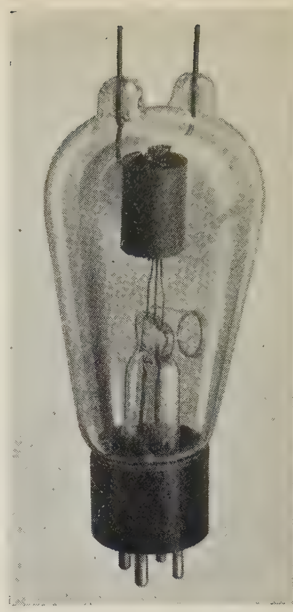


Fig. 7. A tube for use at frequencies up to 350 megacycles

frequency range or in establishing the limiting frequency for oscillations. When the frequency range of oscillation of a tube is extended by an adequate decrease in energy losses and by improvements in electrical design, transit time becomes a dominating factor in the reduction of output power and efficiency and in establishing the limiting frequency of oscillation.

This comes about in 2 ways. In the first place, the relative phase of the alternating grid and plate potentials for best operation must be altered to compensate for the time required for the electrons to travel from the region in which the grid has its greatest effect upon their motion to the region in which their motion has the greatest effect upon the plate current. The available control over these phases is usually insufficient to permit a realization of the optimum adjustment. In terms of the measured characteristics of the tube, the transconductance has become complex. But even with the optimum phase adjustment the efficiency is reduced by losses which occur because of the variations in grid and plate potentials during the transit time. Electrons arriving at the plate will in general have velocities greater than the velocity corresponding to the potential of the anode at the instant of their arrival. The excess energy corresponding to the greater velocity is obtained from the oscillating circuit and is dissipated at the plate in the form of heat. Again in terms of the measured characteristics, the input conductance has been increased above its low frequency value.

The mechanism which enables electrons to take energy from the oscillatory circuit in their passage across the tube is evident from a consideration of a somewhat simplified case as shown in Fig. 4. Assume that the anode is held at a constant positive potential of 100 volts, and that the grid is held at 50 volts positive just long enough to allow an electron to come from the cathode to the grid plane (very near one of the wires), where its velocity will correspond to a fall of 50 volts. The potential of the grid is then suddenly changed to 50 volts negative. The electron will then fall through an additional potential difference of 150 volts, arriving at the anode with a velocity corresponding to 200 volts, producing just twice as much heat as it would have done had the grid potential not been changed during the transit time. This added energy must come from the source which produced the change in the grid potential. In the actual case the change in grid potential is not abrupt but a similar loss occurs. This limits the useful frequency range of a tube to values for which the oscillation period is long compared to the electron transit time.

Special Designs Required for Different Ranges of High Frequencies

Most standard power tubes reach the upper frequency limit of oscillation somewhere in the 10 to 100 megacycle frequency range. For frequencies above this, specially designed tubes are required. The frequency range in which a given design is near the optimum is limited. Therefore, there is a succession of tubes, each rated for a band of frequencies. Characteristics such as a high mutual conductance and a sharp cut-off which make a tube a good oscillator at low frequencies, while still of importance at ultra-high frequencies, are apt to be secondary to the special frequency requirements. Although some progress has been made in the modification of conventially designed water-cooled tubes for use above 100 megacycles, more attention has so far been given

to the development of radiation cooled tubes for this frequency range.

A departure from conventional design with increasing frequency is illustrated by a radiation cooled tube described by McArthur and Spitzer[1] in which the ratio of the plate diameter to the plate length is much larger than for the conventional tube. Radiating fins are employed to compensate for the decrease in heat radiating ability of the plate which would otherwise occur because of its short length. In Fig. 5 is shown a photograph of this tube. It will be noted that the tube electrodes are supported directly from their leads. The complete absence of auxiliary supporting members either of metal or of insulating material and the large size of leads reduce radiation, eddy current, and conduction current losses. That portion of the interelectrode capacities due to the supporting structure is also made small by this method of support.

The interelectrode capacities are given below, together with the corresponding values for the type 242*A* tube, which has the same plate dissipation rating but is designed for use at lower frequencies:

	High Frequency Tube	242*A*
Plate to grid	3 $\mu\mu f$	13 $\mu\mu f$
Grid to filament	2 $\mu\mu f$	6.5 $\mu\mu f$
Plate to filament	1 $\mu\mu f$	4 $\mu\mu f$

The decrease in capacity by a factor of approximately 4 makes possible a much greater improvement in performance in the 60 to 150 megacycle per second frequency range than the corresponding degradation in performance due to the lower mutual conductance and the increased electron transit time resulting from the increased spacing. The material increase in plate impedance makes it necessary to employ an anode potential approximately twice as great with the high frequency tube.

Output and efficiency curves are shown in Fig. 6. (For the sake of uniformity, curves taken from published papers have, in most cases, been redrawn.) The particular shape of the output curve is due to the manner in which the applied anode potential was reduced with increasing frequency to minimize the danger of tube failure from the increased energy losses which occur at high frequencies. The limiting frequency as set by the interelectrode capacities and lead inductances is given by the authors as 230 megacycles. An extension of the efficiency curve to higher values indicates that the tube will probably fail to oscillate before this limit is reached. From this it can be inferred that the decrease in efficiency in the range from 150 to 200 megacycles is due largely to the effect of the relatively large transit time, since the authors' method of arriving at the output by taking the difference between the measured input and the measured plate losses includes circuit and lead losses as a part of the output. A comparison of the data of Fig. 1 and Fig. 6 shows that at 100 megacycles the output of the type 242*A* tube is 2 watts and the corresponding output of the high frequency tube is approximately 86 watts with substantially the same plate loss. This strikingly illustrates the improvement obtained by taking into account the factors which become important in the high frequency range.

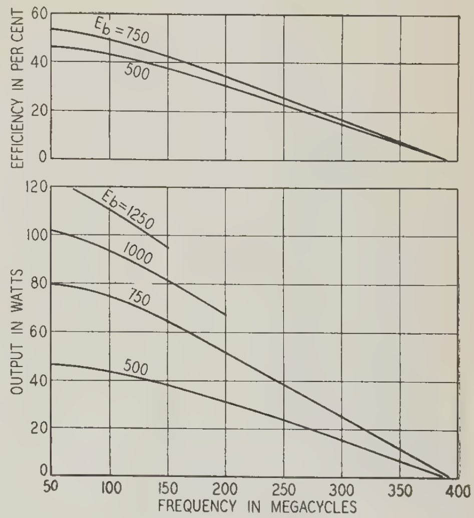
Transit Time Becomes More Important

In extending the frequency range to 300 megacycles the importance of electron transit time becomes relatively greater. It must be kept as low as possible even at the expense of relatively higher interelectrode capacities. In the tube just described for the frequency range around 100 megacycles the reverse procedure is followed; in order to make the interelectrode capacities as small as possible, transit times are increased. Fay and Samuel[2] in a recent paper presented before the International Scientific Radio Union (U.R.S.I.) describe a tube designed for use at 300 megacycles which well illustrates this point. The tube is shown in Fig. 7. It differs from the one previously discussed in the close spacings between elements, particularly between the grid and filament. The lead length is further decreased and lead diameter made considerably larger in order to decrease lead inductance and resistance. The interelectrode capacities are:

Plate to grid	2.5 $\mu\mu f$
Grid to filament	2.0 $\mu\mu f$
Plate to filament	0.67 $\mu\mu f$

While these capacities are substantially the same as for the tube shown in Fig. 5, the limiting frequency, as set by circuit resonance, is somewhat beyond 400 megacycles as contrasted with 230 megacycles for the other tube. This is due, primarily, to the material decrease in lead inductance. The decreased losses resulting from the minimized transit time more than compensate for the increased circuit loss resulting from the required higher charging currents to the interelectrode capacities. Its mutual conductance of 2,200 microohms and the sharp cutoff shown by the static characteristics indicate that those electrical characteristics which are important

Fig. 8. Output and efficiency curves for 2 tubes of the type shown in Fig. 7



1. For all numbered references see list at end of paper.

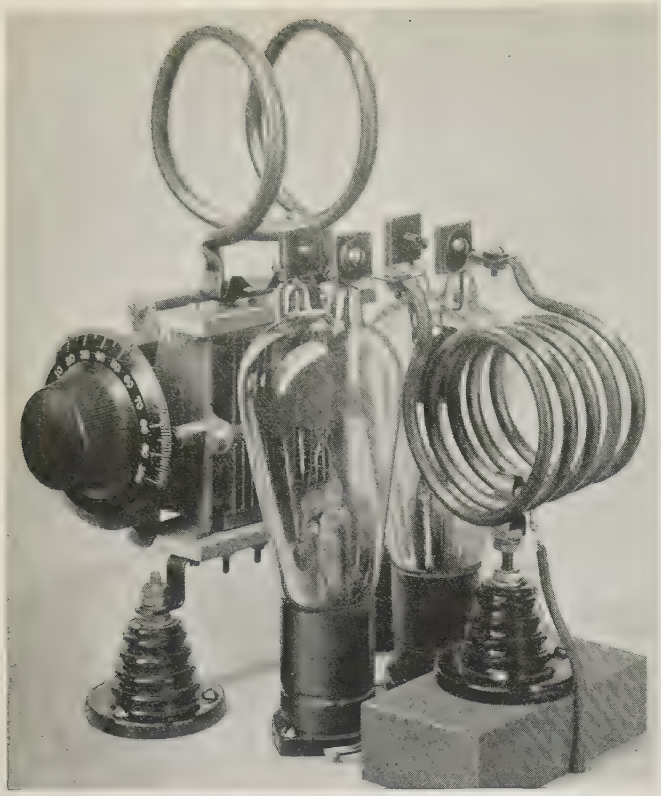


Fig. 9 (left). **A typical push-pull circuit for use at ultra-high frequencies**

A circuit of this type was used to obtain the data shown in Figs. 8 and 11

Fig. 10. **This tube will oscillate at frequencies up to 740 megacycles**

Note the absence of the usual press and the extremely small size of the elements

for efficient oscillators in the low frequency range have not been sacrificed in meeting the requirements of 300 megacycle operation.

Output and efficiency curves for this tube are shown in Fig. 8. These data are for 2 tubes operated in the push-pull circuit shown in Fig. 9. The output shown represents only useful power, since it is the photometrically measured power consumed in a lamp load. It will be noted that, whereas the maximum output at 100 megacycles is 55 watts per tube and the efficiency 50 per cent, corresponding roughly to the 86 watts output at 47 per cent efficiency for the tube of Fig. 5, the output at 200 megacycles is 34 watts at 33 per cent efficiency as compared to less than 10 watts at an efficiency of only a few per cent for the other tube. At 300 megacycles the higher frequency tube gives an output of 13 watts, while the tube of Fig. 5 no longer oscillates. This difference in behavior is due primarily to the decreases in transit time and in circuit losses, and to the more nearly optimum ratio existing between the interelectrode capacities. It is due to a considerably less extent to the increase in the frequency limit set by circuit resonance.

A Still Further Departure in Construction

The tube illustrated in Fig. 10 represents a still further departure from conventional construction with a corresponding increase in the frequency limit. Fay and Samuel report an output of 6 watts per tube at 500 megacycles and a frequency limit of 740 megacycles. Unusual features of the design are: The complete elimination of the usual press, the close spacing of the leads and the special construction of the tube elements, particularly the grid, made necessary by their small size. The grid is in the form of a number of straight wires (parallel and equidistant from the axial filament) supported by cooling collars at each end. The plate, in spite of its small size, can dissipate 40 watts with safety.

The interelectrode capacities of this tube are:

Plate to grid	1.8 $\mu\mu$f
Grid to filament	1.0 $\mu\mu$f
Plate to filament	0.75 $\mu\mu$f

The output and efficiency curves, shown in Fig. 11, were obtained with 2 tubes in a push-pull circuit. The efficiency of the tube is about 28 per cent at 300 megacycles, contrasting with only 18 per cent for the previously discussed tube, while the output is only 8 watts as compared to 13 watts. The higher efficiency suggests that above 300 megacyles 2 of the smaller tubes are preferable to one of the large tubes. The fact that the limiting frequency varies with the applied anode potential indicates that the transit time effect is largely responsible for the decreased efficiency. This suggests modulation difficulties if the tube is used near the upper limit of the frequency range. The outputs and efficiencies in the 400 to 600 megacycle range, although low, represent a substantial increase over the usual values obtained at these frequencies.

The relatively low efficiency at 200 megacycles is due to insufficient filament emission. In order to maintain space charge conditions near the filament, at high frequencies, the electron emission must be large enough to supply not only the actual electron current to the plate but also the charging currents to the grid-filament and plate-filament capacities. In a tube of this small size an increase in the filament emission is possible only by an impractical and unwarranted increase in the filament heating current.

The logical extension of these principles to increasingly high frequencies requires the use of closer and closer interelectrode spacings. Severe mechanical difficulties are encountered. Curiously enough the limiting factor in the power dissipating ability of the tube turns out to be the grid temperature rather than the temperature of the plate as might

be expected. This comes about because of the required close grid-filament spacing, and makes necessary the adoption of some method of cooling the grid. One of the writers has constructed a series of tubes in which the grid is a tungsten helix, each turn of which is attached to a common cooling fin projecting through a slot in the plate. This construction simplifies the mechanical problems involved and provides ample grid cooling. Two of these tubes are shown in Fig. 12. The larger one will deliver 10 watts at 670 megacycles with an efficiency of 20 per cent and the smaller one will deliver one watt at 1,200 megacycles with an efficiency of 10 per cent. These tubes are in no sense commercial, the results representing the limit that has been obtained by specially constructed tubes under controlled laboratory conditions at voltages and currents above those for which the tube would have a long life. With further advances it is reasonable to expect that outputs of this sort will be commercially realizable and that the frequency range of the negative grid oscillator can be extended beyond 1,200 megacycles.

Tubes for Receiving Purposes

For receiving purposes where large outputs are not needed, the ultra-high-frequency requirements are best met by shrinking all the tube dimensions in proportion to the desired wave length. Tubes constructed by Thompson and Rose[3] based upon this principle are shown in Fig. 13 compared in size with the conventional receiving type tube. These tubes make use of parallel plane electrodes, the cathode being oxide coated and indirectly heated, and the grid being in the form of a mesh. A cross-section view of the triode is shown in Fig. 14. This tube will oscillate at frequencies up to 1,000 megacycles in miniature replicas of the customary circuits used at longer wave lengths. A photograph of a complete oscillator is shown in Fig. 15 and the circuit diagram in Fig. 16.

Factors Limiting Ultra-High Frequencies

The limiting factor in the continued extension of the negative grid oscillator to higher and higher frequencies appears to be the dependence of physical size and output power on the operating frequency range. This dependence is well illustrated by the comparison in Fig. 17 of some of the tubes so far discussed with a standard one-kilowatt tube for which the frequency limit is approximately 75 megacycles. Dimensional considerations indicate that the linear dimensions of a series of tubes of optimum design must be decreased in proportion to the operating wave length. Since the heat dissipating ability depends upon the surface area of the plate, the output (assuming the same efficiency) will decrease as the square of the wave length. That this is approximately true for the tubes shown in Figs. 5, 7, and 10 may be seen by reference to Fig. 18 where the outputs as a function of frequency are plotted on a logarithmic scale. The sloping lines are for different values of the ratio of output to the square of the

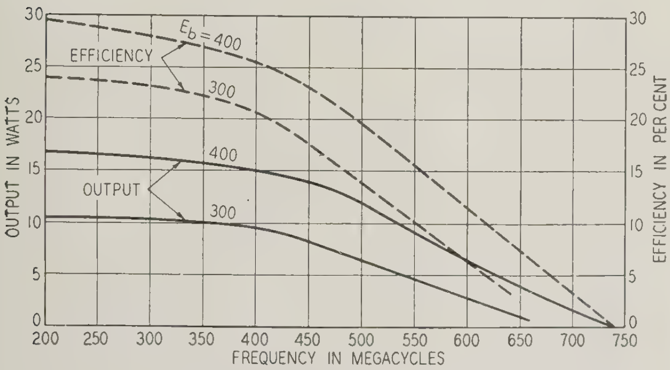


Fig. 11. Output and efficiency curves for 2 tubes of the type shown in Fig. 10

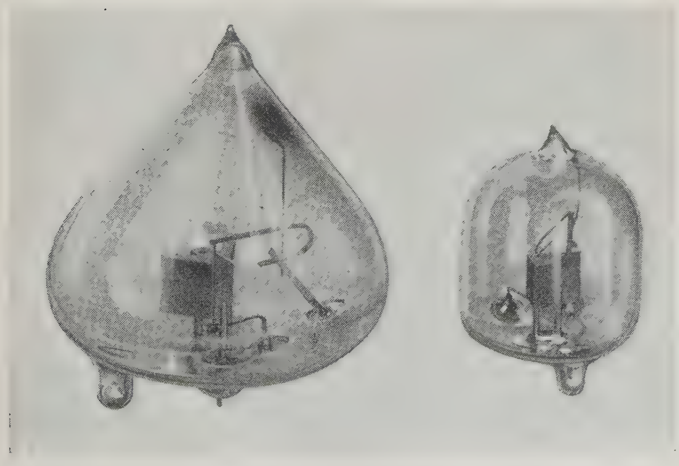


Fig. 12. These tubes represent a further extension in design according to the principles under discussion

The smaller one will oscillate at 1,200 megacycles per second

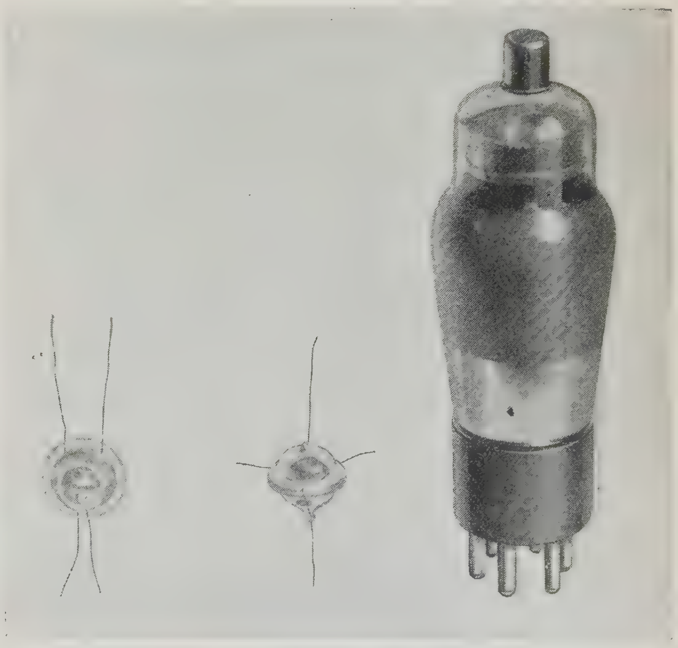


Fig. 13. Receiving tubes of extremely small dimensions

A conventional receiving type tube is shown at the right for comparison

wave length. With radiation cooled tubes patterned after those illustrated, outputs of only a few tenths of a watt at 3,000 megacycles can be expected. If larger outputs are to be obtained, innovations in tube design must be made.

Positive Grid (Barkhausen) Oscillator

As first reported by Barkhausen and Kurz[7] in 1920, oscillations at frequencies greater than 300 megacycles can be produced by most high-vacuum triodes having symmetrical cylindrical structures when the grid is operated at a fairly high positive potential and the plate is held at or near the cathode potential. When so used they are variously known as oscillators of the Barkhausen and Gill-Morell[8] types after the earliest experimenters, or oscillators of the positive grid or retarding field type to designate the arrangement of the electrode potentials. The relative ease with which such oscillations can be obtained at frequencies above 300 megacycles by

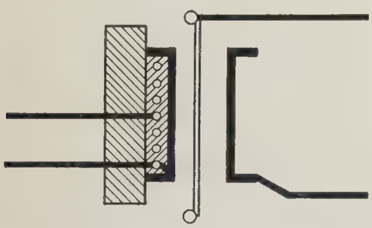


Fig. 14. A sectional view of the triode developed by Thompson and Rose

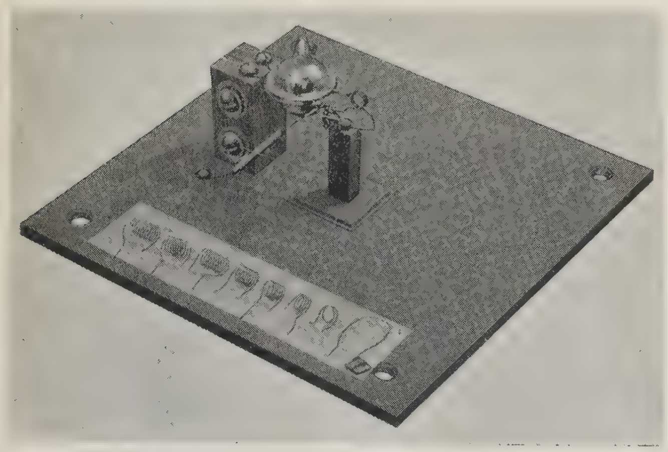


Fig. 15. A complete oscillator using a miniature receiving tube

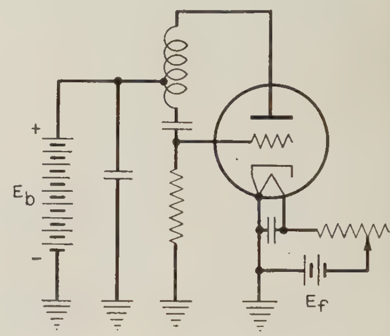
the use of conventional tubes, and the widespread interest in this frequency range for communication purposes, have led to the appearance of a large number of papers on the experimental and theoretical aspects of such operation.

With the positive grid oscillator there are found to exist preferred frequencies of operation fixed by the electrode spacings and the applied electrode potentials. For the lowest preferred frequency modes of oscillation the relationship is such that the period of one complete oscillation is approximately equal to the total transit time of an electron which fails to strike the grid on its first transit, is retarded and finally turned back by the plate potential, and again missing the grid, returns to the cathode. Under these conditions the relationship,

$$\frac{E_g}{n^2} = \text{constant},$$

is found to hold approximately, where E_g is the applied grid potential, n is the frequency, and the constant is a function of the tube geometry. Other high frequency modes of oscillation can be obtained. One of these is particularly easy to excite if the grid of the tube is in the form of a simple helix. The important rôle played by the electron transit time in determining the frequency of the positive grid oscillator contrasts sharply with the minor rôle

Fig. 16. The circuit diagram of the oscillator shown in Fig. 15



it plays in determining the frequency of the negative grid oscillator.

For maximum output it is necessary to adjust the tuning of the external circuit to correspond to the preferred frequency fixed by the applied electrode potentials. The relative dependence of the frequency upon the circuit tuning and on the applied electrode potentials varies greatly with the design of the tube. In any case the improper adjustment of either parameter results in a marked decrease in output. In general it appears that the better the tube design and the higher the operating efficiency the greater will be the dependence of frequency upon circuit tuning and the less will be its dependence upon the applied electrode potentials.

The most efficient operation of the positive grid oscillator is obtained when the space current is limited by the cathode emission, as contrasted with the most efficient operation of the negative grid oscillator when the current is limited by space charge. Not only must the space current be emission limited but it must have a fairly critical value. This makes it necessary to adjust the cathode temperature critically. Since the cathode emission characteristics are apt to change with time, frequent readjustments of the cathode temperature are usually required.

No completely satisfactory and generally accepted theory of the positive grid oscillator has as yet been given. Many theoretical papers dealing with the mechanism of oscillation have been published. Some of these papers resort to pictorial explanations which, from their very nature, must leave out certain basic factors. Readers interested in a résumé of the various theories are referred to the excellent review by Megaw[13] and to the original papers. It

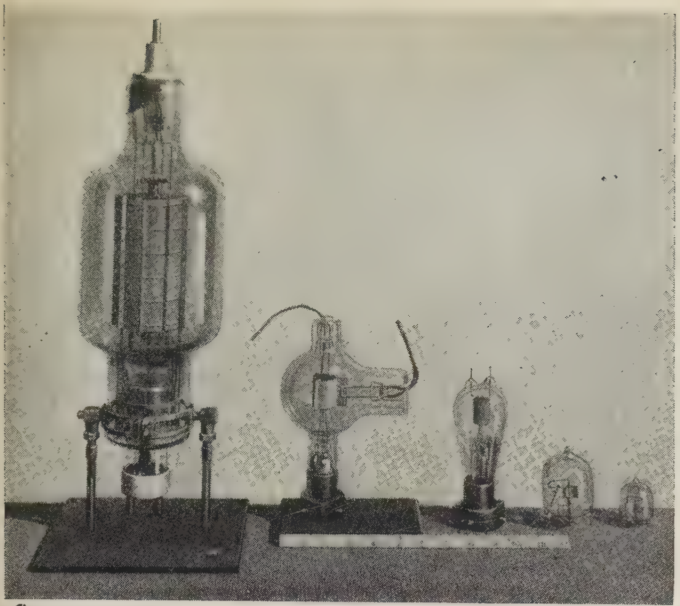


Fig. 17. Some of the tubes, previously discussed, compared in size with a lower frequency tube on the left

is now recognized that any accurate theory must be based upon a general consideration of all the forces acting upon the electrons in their flight between the electrodes. This may take the form of either a particular solution of the classical electromagnetic equations for the conditions within the tube or an analysis of the energy contributions due to individual electrons in their passage across the interelectrode space.

Construction of a Positive Grid Tube

A representative positive grid tube of current design described by Fay and Samuel[2] before the International Scientific Radio Union is shown in Fig. 19. This tube differs from the conventional negative grid tube primarily in the construction of the grid and in the arrangement of the leads. While designed primarily for use in the frequency range from 500 to 550 megacycles, it illustrates the general problems encountered in the construction of the positive grid oscillator of this type for any frequency range.

The grid consists of a number of parallel wires supported by cooling collars at each end, the so-called squirrel cage construction. It will withstand 150 watts heat dissipation safely, and provides a minimum of circuit inductance and resistance. The grid diameter is fixed by the frequency for which the tube is designed and by the desired operating potential, such that the relationship

$$d_g = \frac{K_1\sqrt{E_g}}{n} \tag{1}$$

is approximately satisfied, where d_g is the diameter of the grid, K_1 is a constant, n the frequency, and E_g the applied grid potential.

An indefinite increase in output at a fixed frequency by the simultaneous increase in the grid diameter and in the applied grid potential is not possible because of the limited permissible grid dissipation per unit area. The optimum grid current is found to follow roughly a $^3/_2$ power law, that is

$$I_g = K_2\,\frac{E_g{}^{3/2}}{d_g} \tag{2}$$

so that the grid power will increase as the fourth power of the grid diameter while the grid area and hence the heat dissipating ability only increases as the first power of the diameter. Because of this an upper limit in output exists, fixed by the maximum permissible heat dissipation per unit area for the grid structure. The optimum grid diameter will vary directly with the wave length for which the tube is designed, and if the ratio of the grid length to its diameter is maintained constant, the maximum available power output (assuming the same efficiency) will vary as the square of the desired wave length.

Circuit of a Positive Grid Oscillator

In Fig. 20 is shown a diagram of a positive grid tube of the straight-wire-grid type and its associated

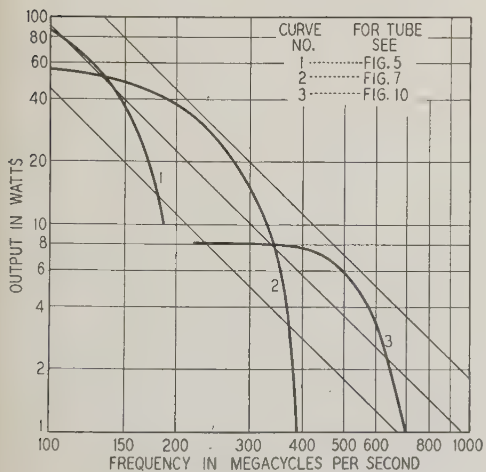
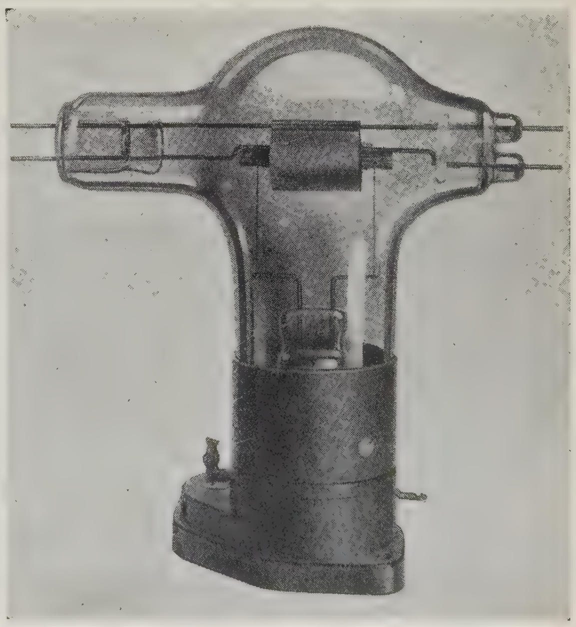


Fig. 18 (left). A comparison plot of the outputs obtained with the tubes of Figs. 5, 7, and 10

The sloping lines are fixed values of the ratio of output to the square of wave length

Fig. 19 (right). A positive grid oscillator designed for the frequency range from 500 to 550 megacycles



circuit. Tuned circuits, in this case in the form of so-called Lecher systems, are connected between the grid and plate leads, extending approximately a half wave length (30 cm) beyond the lead seals. Because of the existence of preferred frequencies of operation fixed by the potentials applied to the tube electrodes, distributed-constant circuits, if used, may be operated at frequencies corresponding to harmonic modes of oscillation. In this case the length of the leads within the tube envelope has been adjusted so that the glass seals come at or near potential nodal points for the Lecher systems of which the leads form a part. This minimizes dielectric losses in the glass. The effective paralleling of the 2 sets of leads greatly reduces the resistance losses,

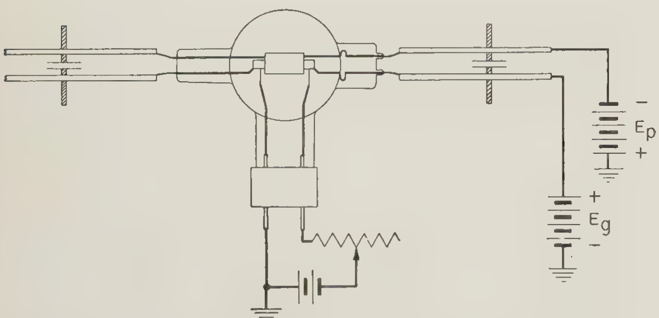


Fig. 20. A typical positive grid oscillator circuit

while the balanced arrangement decreases radiation losses. Strict attention to these details is required because of the already low efficiency of the mechanism of generation.

Characteristics of Positive Grid Oscillators

The dependence of output and anode efficiency on frequency is shown in Fig. 21. These data were taken by adjusting the circuit tuning, filament current, and the grid and plate potentials to their op-

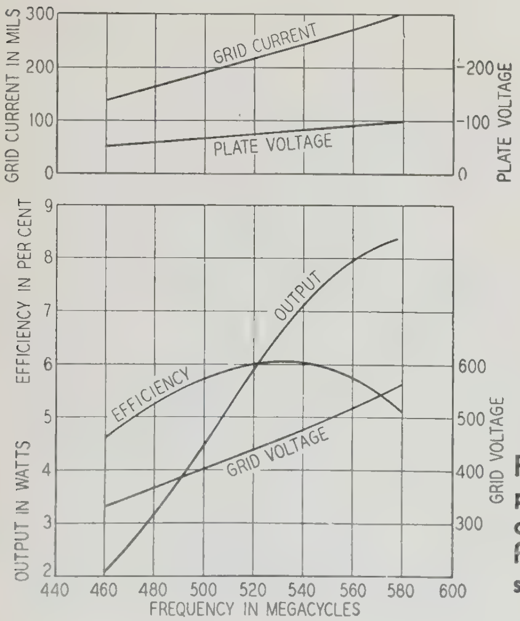


Fig. 21. Output and efficiency curves for the tube shown in Fig. 19

timum values for each frequency. The curve showing the grid voltage will be observed to follow eq 1 above, at least roughly, and a similar correspondence will be observed between the curve for the grid current and eq 2. Some variation in the required

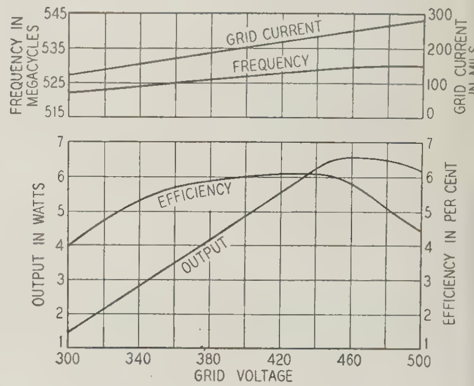


Fig. 22. Result of variation of grid voltage, tuning fixed, on tube of Fig. 19

negative plate potential is observed. A maximum efficiency will be noted at a frequency of approximately 530 megacycles. The output, however, continues to increase with increasing frequency, the limit in output as well as in frequency being set by the safe grid dissipation. The outputs over the 500 to 600-megacycle range vary from 4.5 to 8 watts, comparing with outputs from 6 to 3 watts for the

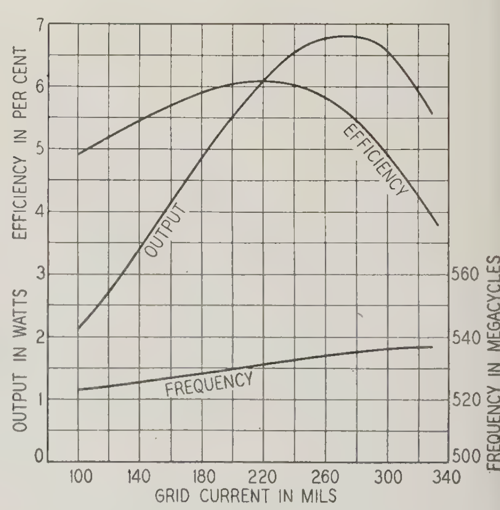


Fig. 23. Result of variation of grid current, other adjustments fixed, on tube of Fig. 19

f = 532 megacycles
E_G = 450 volts

negative grid tube. The low efficiencies of 5 to 6 per cent are to be compared with the somewhat higher efficiencies of 19 to 11 per cent for the negative grid type tube.

The influence of the grid voltage on the frequency and on the output and efficiency is shown by the curves in Fig. 22. These data are for a fixed circuit tuning, the grid voltage being adjusted to the values indicated. This corresponds to the condition that might obtain if a grid voltage modulation scheme were to be used. The lack of linearity of the output curve and the large shift in frequency indicate that amplitude modulation by this method

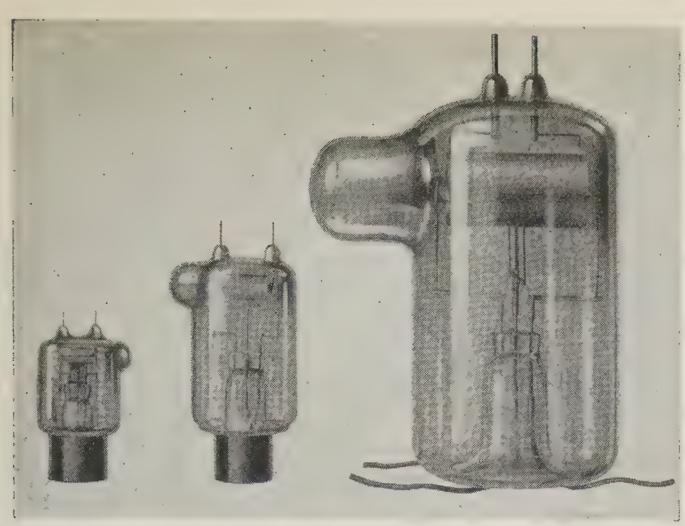


Fig. 24. Three optimum positive grid oscillators of the spiral grid type

Smallest tube designed for 2,500 megacycles, largest for 500 megacycles

would be unsatisfactory. The frequency shift, large as it is, is much less than the shift observed in tubes of poorer design and correspondingly lower efficiency.

The dependence of the output and efficiency as well as frequency upon the grid current is shown in Fig. 23. These data were taken with a grid potential of 450 volts and a fixed circuit adjustment corresponding roughly to a frequency of 532 megacycles. The current to the grid was varied by adjusting the temperature of the filament. The maxima observed in both the output and the efficiency correspond to conditions for which the grid current is limited primarily by the available emission rather than by space charge. As conditions corresponding to complete space charge are approached the output and efficiency fall off rapidly. The limit on the permissible grid dissipation prevents the extension of these curves to the condition of complete space charge. Because of this dependence of output on grid current, the adjustment of filament temperature is extremely critical.

At lower frequencies the efficiency of operation of a correctly designed positive grid tube is substantially the same as that exhibited by this tube. The negative grid oscillator on the other hand, as has been shown, increases both its output and efficiency rapidly with decreasing frequency. The positive grid oscillator is, therefore, at an increasing disadvantage at lower frequencies. With the present state of development, the negative grid oscillator will give larger outputs with higher anode efficiencies at all frequencies less than about 300 megacycles.

For frequencies much higher than 600 megacycles, it is found that the power input requirements for efficient operation of tubes having grids of the straight wire type are in excess of that which can be tolerated in the grid structures. Operation at very much less than optimum input results in considerable decrease in output as indicated in Fig. 25.

Spiral Grid Barkhausen Tubes

If the grid of a Barkhausen oscillator is in the form of a simple helix, oscillations at frequencies greater than those predicted by the relationship of eq 1 are readily obtained. When so constructed they are called spiral grid Barkhausen tubes. Some experimental models are shown in Fig. 24. The tubes used in the Lympne to St. Inglevert "microray link" are of this general type.[14] Such tubes have been used to produce oscillations up to 3,000 megacycles.

Because of the fact that the severe limitation on the optimum grid diameter is modified by the presence of a tuned circuit within the tube formed by the helical grid helix, tubes of this type are particularly useful at frequencies above 600 megacycles. The former restriction on grid diameter is replaced by the requirement that the expanded length of the grid spiral be approximately 1.24 times the wave length at which the maximum output is required, and that there be a correct proportioning of the other dimensions of the tube. The dependence of wave length on the grid wire length is illustrated by the experimental data in Table I covering a frequency range from 460 megacycles to 2,220 megacyles. Graphic evidence of the independence of shape is shown by the largest and the smallest tube shown in Fig. 24 for which the dimensional ratios are nearly the same. The largest tube delivers several watts at 500 megacycles, while the smallest one delivers only a few tenths of a watt at 2,500 megacycles. The efficiency in both cases is about one per cent. These dimensional considerations lead to the conclusion that there exists a maximum output at any given wave length for a tube of a given design and that this output is proportional to the square of the optimum wave length. From this it appears that the only advantage offered by the spiral grid tube

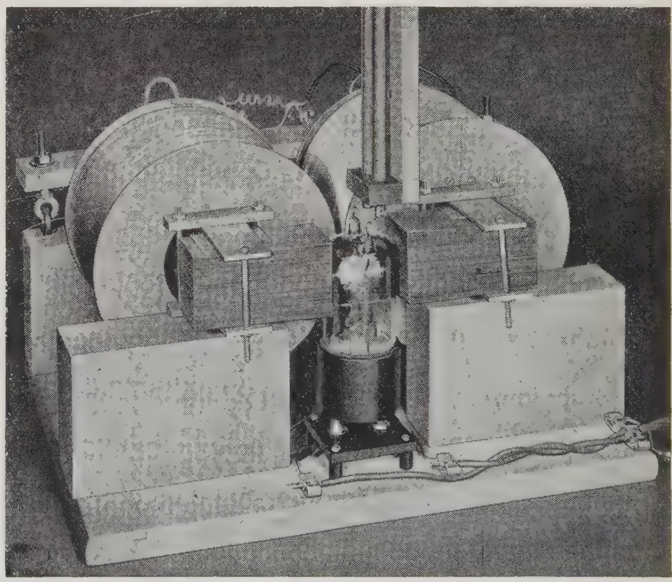


Fig. 25. An experimental model of the split-plate magnetron showing a possible arrangement of the magnetic field

over the other type is the simplification in mechanical design which permits the construction of rigid grid structures capable of high energy dissipation for the higher frequency range.

The external tuned circuit for the higher frequency mode of oscillation takes the form of a Lecher system connected between the 2 grid terminals. When so connected the dependence of frequency upon circuit tuning is pronounced, as contrasted with the negligible dependence observed if the Lecher system is connected between the plate and the grid. When oscillating in the higher frequency mode the spiral grid tube shows only a comparatively small dependence of frequency on grid potential and this may be compensated by a proportional change in plate potential. This, coupled with the fact that the output increases rapidly with increasing grid potential, makes it possible to apply various schemes of amplitude modulation. Characteristics of the type shown in Figs. 21, 22, and 23 for the straight-wire-grid tube cannot be taken except for a limited portion of the range due to the inability of the grid to dissipate

Table I—Dependence of Wave Length on Grid Wire Length for Barkhausen Oscillator With Helical Grid

Grid Wire Length in Cm.	Optimum Wave Length in Cm.	Ratio
16.3	13.5	1.21
18.6	18.6	1.00
19.7	14.5	1.36
20.4	18.0	1.13
21.4	17.5	1.22
21.3	25.0	0.85
22.3	20.2	1.10
25.2	18.6	1.35
30.6	25.0	1.22
32.0	23.6	1.36
32.0	25.5	1.25
33.4	25.0	1.33
42.6	29.0	1.47
42.6	29.5	1.44
42.6	30.2	1.41
42.6	30.7	1.38
53.2	43.5	1.22
80.0	65.0	1.23
Average		1.24

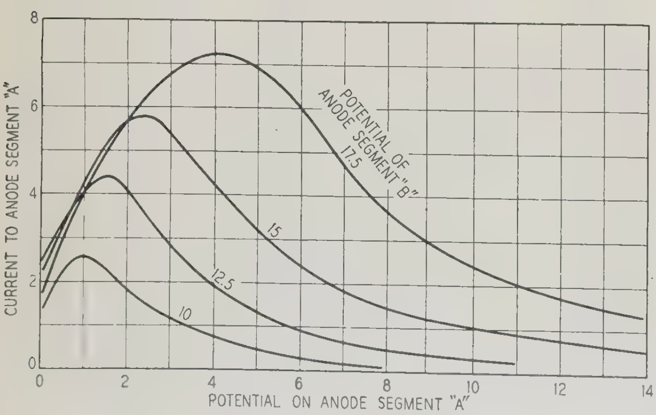


Fig. 26. Static characteristics of a split-plate magnetron

Magnetic field set for cut-off at potential of 1.45 volts. All values in arbitrary units

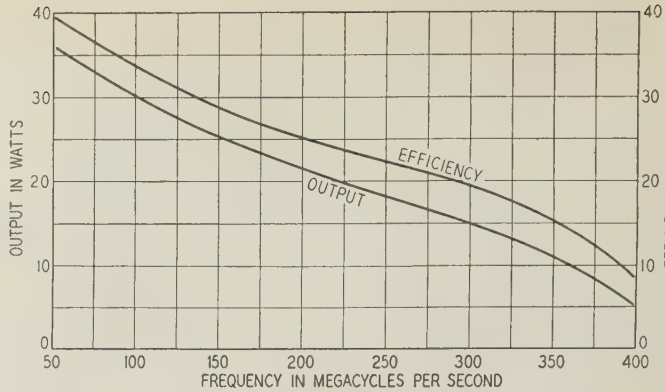
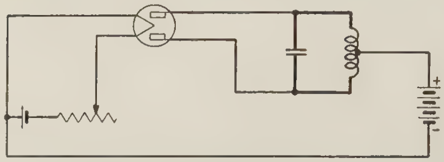


Fig. 27. Output and efficiency curves at different frequencies for split-plate magnetron

Anode potential—1,500 volts
Magnetic field—600–800 gausses



Data for Fig. 27 taken in this type of circuit

Fig. 28. Oscillation circuit of split-plate magnetron

the energy required in the upper portion of the grid voltage or grid current ranges.

While the spiral grid tube will also oscillate in the lower frequency mode, its efficiency and output are considerably lower than the corresponding values for the straight-wire-grid tube previously discussed. Its field of usefulness is, therefore, largely limited to the higher frequency mode of oscillation in the frequency range above 600 megacycles.

The "Magnetron" Oscillator

The "magnetron" in its simplest form consists of a cylindrical diode or 2-electrode tube, with a uniform magnetic field in the direction of the electrode axis. The original type of tube has been largely superseded for ultra-high-frequency generation by the so-called split-plate magnetron, first used by Okabe,[18] in which the cylindrical anode is divided longitudinally into 2 (or more) segments to the terminals of which is connected the tuned circuit. Such a tube is shown in Fig. 25.

In the frequency range from 300 to 600 megacycles the split-plate magnetron compares favorably with the negative grid tube both in output and in anode efficiency. Its use has been limited because of the complicating factor of the magnetic field, and the attending modulation difficulties. For frequencies higher than 600 megacycles the magnetron provides larger outputs than those so far reported by other means. It has been used at frequencies up to 30,000 megacycles, a value well above that so far reported for any other type of vacuum tube.

The magnetron depends for its operation upon the curvature of the electron orbits produced by the magnetic field. As first shown by Hull[15] in 1921, a

critical field exists beyond which the anode current falls off rapidly to zero. This field is given by the relationship

$$H = \frac{6.72}{R}\sqrt{V} \quad (3)$$

where R is the anode radius and V is the potential of the cylindrical anode with respect to an axial filament. Although the original magnetron of Hull and Elder made use of variations in the magnetic field in its operation as a generator, it was soon discovered that oscillators could also be produced with steady fields by 2 somewhat different mechanisms. The one, first pointed out by Habann,[16] makes use of a negative resistance effect observable in the static characteristics and the other, first described by Zácek,[17] involves the electron transit time in a way quite analogous to the way in which it is involved in the positive grid triode. Both mechanisms have been used to produce oscillations at ultrahigh frequencies.

Negative Resistance Type

Data reported by McArthur and Spitzer[1] on a split-plate magnetron tube are illustrative of the negative resistance type of behavior. Static characteristics taken by varying the potential of one anode with the magnetic field held constant for different values of the potential on the other anode are shown in Fig. 26. The pronounced negative resistance effect is obvious. This negative resistance characteristic can be utilized in producing oscillations.

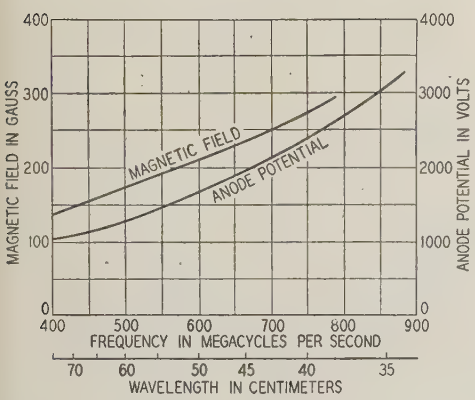


Fig. 29. Relation of magnetic field and anode potential to frequency of oscillation in magnetron oscillator of second type

Output and efficiency curves for this tube as an oscillator are shown in Fig. 27. These data were obtained by connecting a "tank" circuit, tuned to the desired frequency, across the 2 anodes, as shown in Fig. 28. Each anode delivers energy to the oscillating circuit during alternate half-cycles, so that in effect, it is equivalent to a push-pull oscillator. The limiting frequency as set by the interelectrode capacities and lead inductances (corresponding to the similar limit for the negative grid tube) is 450 megacycles. The decrease in output before this limit is reached is due to resistance and radiation losses and to the effect of electron transit time.

The magnetron, as contrasted with the negative grid tube, will oscillate with circuits having a high decrement. However, for its most efficient operation the effective anti-resonant impedance of the tuned circuit when loaded must be approximately 10 times the value required by a triode with the same anode dimensions. The load resistance that can be obtained at high frequencies is only a fraction of this value, so that the efficiency becomes increasingly less with higher frequencies. A further limitation is due to the fact that the electron current is concentrated on only a small part of the anode surface. This reduces the safe anode dissipation unless the anode is designed to have a high thermal conductivity. Because of these limitations, the ratio of output to the interelectrode capacity may be only slightly more favorable than the corresponding ratio for a triode of the same anode dimensions.

Type Depending on Electron Transit Time

When the magnetic field of a split-plate magnetron is adjusted to near the critical value given by eq 3, oscillations can be produced whose frequency will depend primarily upon the time of flight of electrons between filament and anode in a way closely resembling the behavior of the positive grid oscillator in its lower frequency mode of oscillation. For best output, the field must be above the critical value. To fix the time of flight and hence the frequency of oscillation, the magnetic field and plate voltage must be adjusted to certain values roughly expressed by the empirical relationship

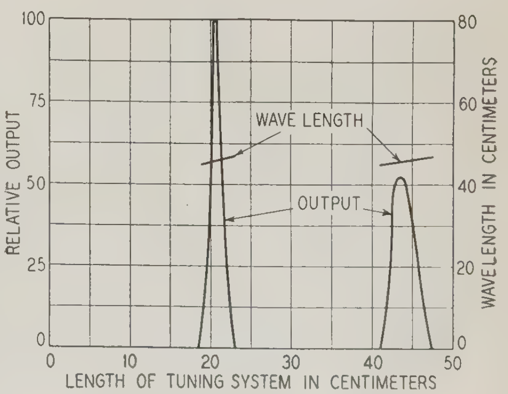
$$\lambda H = 13{,}100 \quad (4)$$

where λ is the wave length in centimeters and H is the field strength in gausses, which must also satisfy eq 3. It is found that for best operation the magnetic and electric fields within the tube should not be exactly perpendicular. This lack of perpendicularity may be achieved either by tipping the magnetic field relative to the tube axis or by introducing end plates within the tube and maintaining them at a fixed positive potential.

Kilgore[19] has given complete information concerning this type of oscillator. In Fig. 29, taken from his paper, is shown the dependence of field strength and anode potential on the desired frequency. The existence of a preferred frequency fixed by these values is confirmed by the data in Fig. 30 relating the output and wave length with the

Fig. 30. Relation of wave length and output to length of tuning system in magnetron oscillator of second type

Anode potential—2,000 volts
Magnetic field—254 gausses



length of the attached Lecher system. The decreased output shown at the second peak is due to the added losses introduced by the extended length of the system. The outputs shown on these curves are not in watts, but represent relative readings of the field strength near the oscillator. With optimum adjustments 7 watts at 715 megacycles is reported, the efficiency being about 8 per cent. The dependence of output and frequency on the applied anode potential is shown in Fig. 31, and the dependence of frequency on the current in the magnetic field coil in Fig. 32. The importance of the adjustment of the field angle is shown by the data in Fig. 33.

An output of 2.5 watts at 3,160 megacycles has been reported by Wolff, Linder, and Braden.[22] They find that the efficiency of the tube is much improved by using end plates in place of the tipped magnetic field. Cleeton and Williams[21] have been able to obtain oscillations at 30,000 megacycles with a magnetron tube.

Amplification

The use of the conventional thermionic triode as an amplifier greatly exceeds its use as an oscillation generator in communication applications. Its ability to amplify has contributed much more to the development of our present-day long distance communication, whether by wire or by radio, than has its ability to oscillate. The complete utilization of ultra-high frequencies as carrier channels in communication will also, no doubt, be dependent upon the development of suitable amplifiers for this frequency range. Although certain forms of pseudo-amplification are possible with tubes of the Barkhausen and magnetron types, the negative grid triode and multi-element tubes derived therefrom are the only devices available for very high frequencies which will amplify in the sense that the output is an enlarged undistorted replica of the input.

As the frequency of operation of the negative grid triode is increased, difficulties in securing stable operation as an amplifier and in realizing the full gain indicated by the tube constants are encountered. These difficulties, as is well known, are in the main due to the tendency of the amplifier to oscillate or "sing" because of feed-back through the grid-plate capacity. This may be overcome either by the introduction of a compensating capacity somewhere in the circuit, so-called neutralization, or by the introduction of an electrostatic shield or screen within the tube envelope between the grid and plate, giving the screen-grid tetrode. Neutralization schemes fail at very high frequencies because of the inductance of the tube leads which makes difficult the correct location of the neutralizing capacity and because of transit-time effects which shift the phase of the needed compensation. However, conventional screen-grid tetrodes and pentodes are available which function satisfactorily over the major portion of the frequency range covered by the conventional 3-element tube as an oscillator.

For frequencies above approximately 60 megacycles specially designed tubes are required. Because of the similarity in the special frequency requirements, it is expected that there will be found a succession of multi-element tubes for amplification use, each rated for a band of frequencies, patterned after corresponding triode oscillators. The special frequency requirements for the amplifying tube are even more severe than those for the triode oscillator, so that the multi-element amplifying tube will in general cease amplifying at a frequency somewhat lower than the frequency limit of oscillation of the corresponding triode oscillator.

Thompson and Rose[3] have described small screen-grid tubes which will amplify at frequencies of 300 to 400 megacycles. One of these tubes is shown in Fig. 13. Their characteristics are similar to those of the conventional screen-grid tube in many respects. The very great reductions in interelectrode capacities, lead inductances, and transit time make

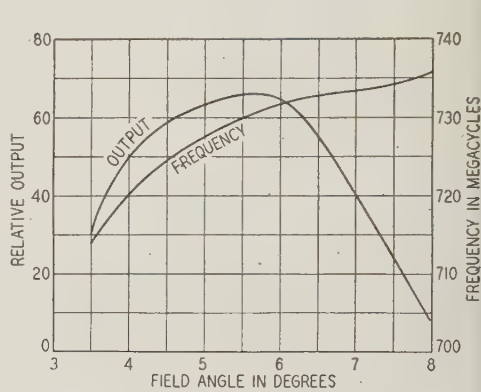


Fig. 33. Relation of output and frequency to field angle in magnetron oscillator of second type

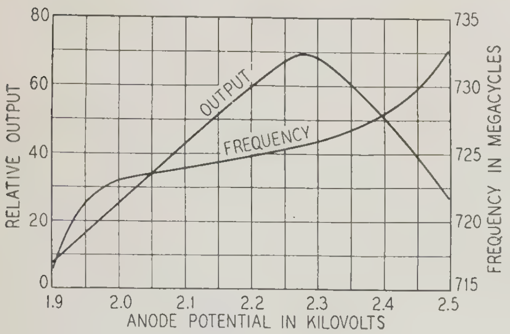


Fig. 31. Relation of output and frequency to anode potential in magnetron oscillator of second type

Field current—0.59 amp
Anode current—0.04 amp
Field angle—5 deg

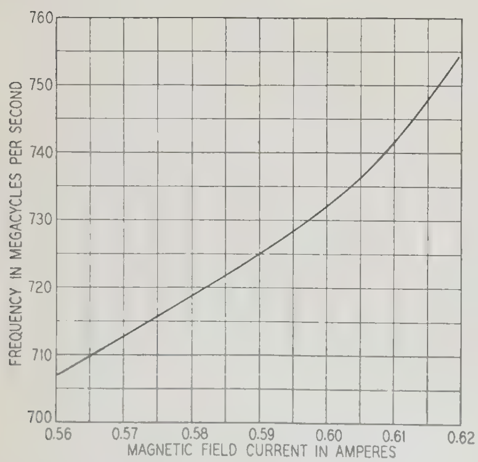


Fig. 32. Relation of frequency to magnetic field current in magnetron oscillator of second type

Anode potential—2,200 volts
Anode current—0.040 amp
Field angle—5 deg

possible the construction of receiving circuits using tuned radio frequency amplification at these very high frequencies. The ratio of the frequency limits of the corresponding triode as an oscillator (1,000 megacycles) to the frequency at which amplification was reported (400 megacycles) is typical and illustrates the apparently inevitable failure of the amplifier to keep pace with the oscillator in the struggle toward higher and higher frequencies.

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The "Thyratron" Motor

A new type of motor in which a scheme involving electronic tubes is used to perform a function similar to that of a commutator is described in this paper. The motor operates at variable speed and is supplied from a 3-phase power system. A 400-hp motor of this type has been built and is ready for commercial use.

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THE newly developed "thyratron" motor described herein is analogous to a commutator motor because a group of "thyratron" tubes takes the place of the commutator and functions to commutate the current. It belongs to the group of developments which are based upon the discovery that the starting of the anode current in a gas arc rectifier could be controlled by a third electrode. Vapor electric devices such as grid-controlled gas-filled or mercury-vapor-filled electronic tubes, based upon this principle, are on the market under the trade name of "thyratron."

The thyratron set which is an essential part of the motor equipment has 2 distinct functions. One is grid controlled rectification and the other is commutation. Each of these functions of the thyratron set has a significance in the practical application of the motor. Through the commutator functions, a motor is made available which operates on an a-c power supply but has smooth variable speed torque characteristics like a d-c motor without any reference to synchronism with the a-c system. The grid controlled rectifier function gives a motor which has continuous power control from standstill to maximum speed. This power control has delicacy, quickness, and accuracy which is superior to anything heretofore available. It may be operated manually or with remote control, and lends itself well to automatic control for regulating speed and power for coördination with other machinery.

ARRANGEMENT OF THE THYRATRON MOTOR

The functioning of the thyratron motor can be best understood if it is looked upon as a species of d-c motor. The elements of a d-c motor are a d-c

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power supply, a commutator, an armature, and a field. In the new motor each of these elements can be identified. A set of thyratron tubes takes the place of the commutator. The armature is stationary and the field is rotating, and the motor has a structural resemblance to the synchronous motor, but nevertheless the functioning of the armature and the field can best be explained in terms of the d-c motor. The d-c power supply can also be identified although it is not so apparent on the surface.

The actual power supply used in the developmental arrangement as shown in Figs. 1 and 2 is 4,000 volt, 3 phase, 60 cycle. With reference to this power supply the thyratron tubes act as a rectifier with an output which appears in the form of direct current. The same set of tubes serve to guide the flow of direct current successively through the different sections of the armature windings like the brushes and segments of a d-c commutator. This double functioning of the thyratron tubes may seem a little confusing at the first instant but this matter can be cleared up by considering for a moment an arrangement as shown in Fig. 3 in which one set of tubes is used for rectification and another set of tubes is used for commutation. Motors have been operated successfully in this way, but the first arrangement is preferable for the practical purpose which is now being considered because of its high torque starting characteristics, which will be explained later under the theory of commutation.

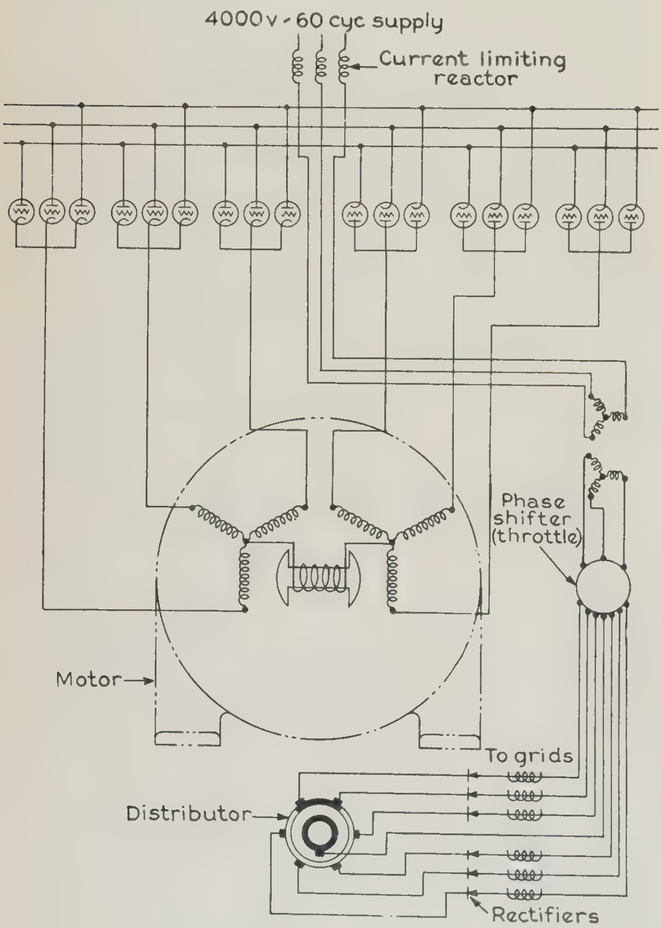


Fig. 1. Simplified diagram of connections of thyratron motor with grid circuit omitted

Consideration of the second arrangement with one set of rectifying tubes and one set of commutating tubes is, however, helpful for the purpose of explanation. The rectifier tubes functioning with the conversion ratio of this type of rectifier transforms the 3-phase a-c power into about 5,000-volt direct current. The rectifier is grid controlled so that the output voltage may be adjusted by the operator to any desired value between zero and full voltage. In this respect the new motor has a distinct advantage over the conventional d-c motor which always consumes power at full voltage unless part of this power is wasted in resistance. The controlling grids of the rectifier, on the other hand, vary this voltage from zero to maximum without any loss of power.

The commutating tubes have a function corresponding to the brushes and segments of the commutator making contacts successively to different portions of the armature winding. Each tube has a cathode and an anode, one of which may be considered as a commutator segment and the other as the brush. The brush and the commutator segment are in contact only at certain times and in analogy

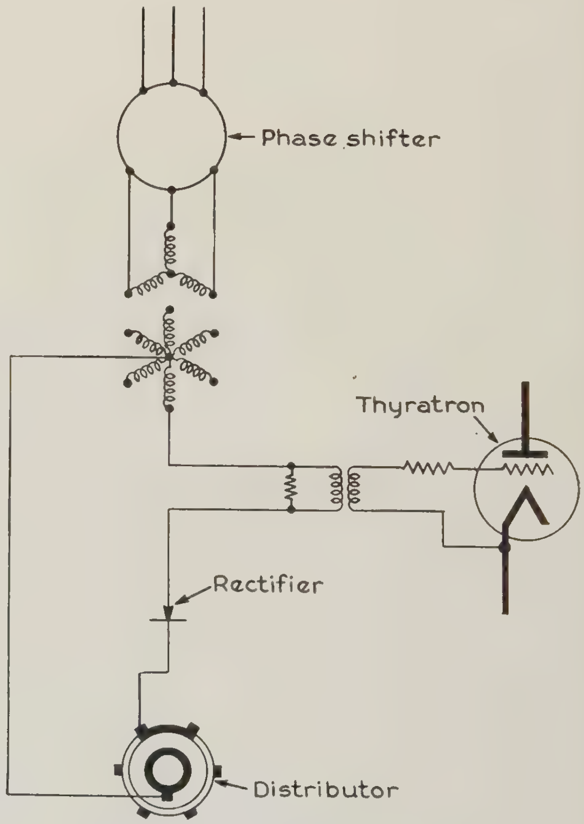


Fig. 2. Thyratron motor grid circuit

with this the grid control functions in such a way that electrical contacts between the cathode and the anode are established only when desired.

When these separate functions of rectification and commutation are understood it becomes easier to analyze the arrangement which is being used whereby each tube performs all these functions at the same time. As seen by the diagram in Fig. 1, the tubes are arranged in groups of 3 with reference to the

power supply and each of these groups functions exactly like a single rectifier tube in Fig. 3. With reference to the motor the tubes are also arranged in groups of 3 but in a different order; and with reference to the motor, the tube groups function like the commutator tubes in Fig. 3. While each tube has only one grid, it has 2 distinct grid controls, one of which functions as a rectifier control and the other as a commutation control. To accomplish this result it was necessary to find some method of combining these 2 grid controls in such a way that

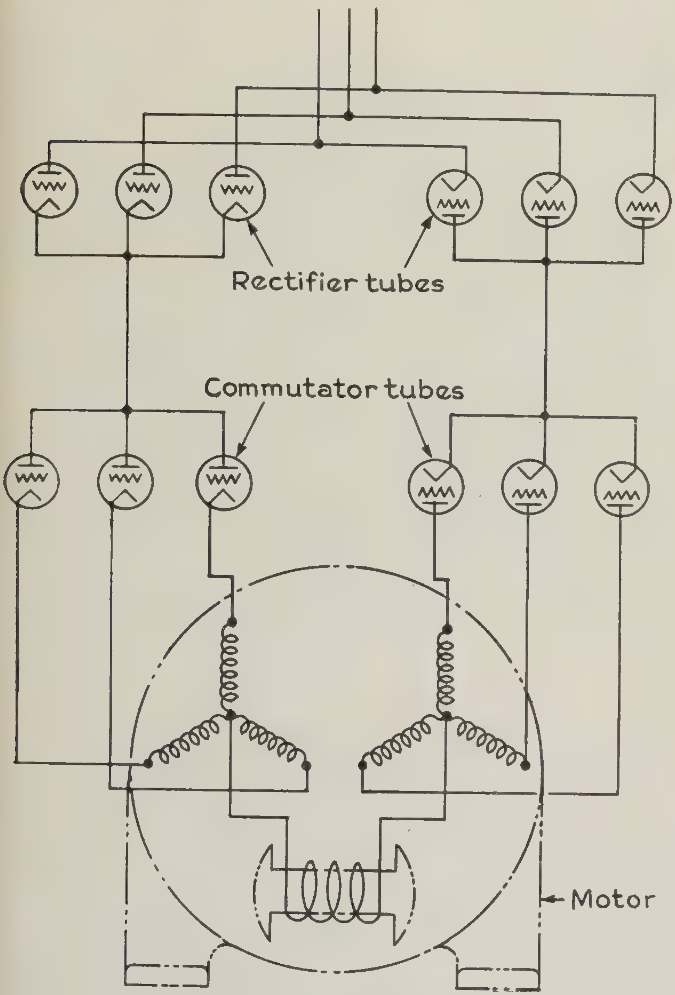


Fig. 3. Equivalent circuit with separate rectifying and commutating tubes

the 2 functions do not conflict with each other. This has been accomplished by the grid control circuit shown in Fig. 2. The rectifier control is of the nature of a phase shifter and the commutation control is in the nature of a distributor. When the phase shifter delivers a positive voltage and the distributor at the same time makes contact, a circuit is closed which impresses a positive voltage on the grid and thus makes the tube conducting. Whenever the phase shifter delivers a positive voltage but the distributor does not make contact, or whenever the distributor makes contact while the phase shifter delivers a negative voltage the tube remains nonconducting.

The choice of the tube which is to be conducting

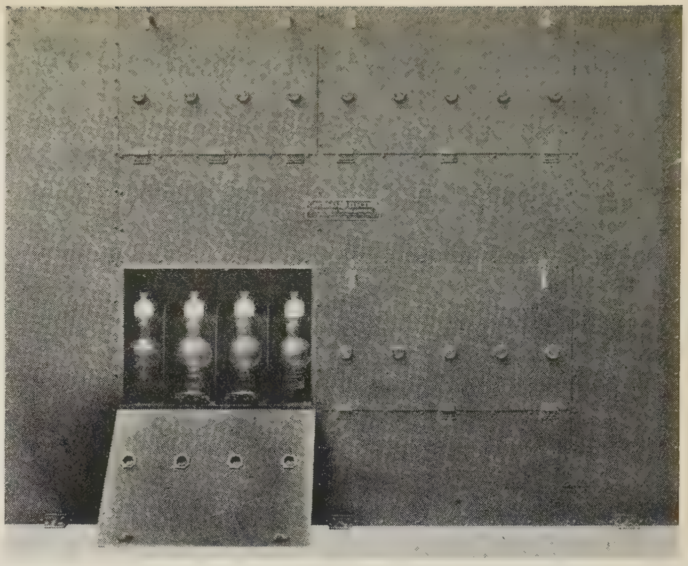


Fig. 4. Thyratron control unit

at any instant is thus determined by the rectifier control and the commutation control in combination in such a way that those 2 controls do not conflict with each other, but the rectifier control determines the path of the current flow exclusively in the power supply circuit, and the commutation control determines the path of the current in the motor circuit.

The assembly of the thyratron tubes of a 400-hp thyratron motor designed for commercial use is shown in Fig. 4. In Fig. 5 is shown the operation board and controller, while the motor proper with the distributor mounted at the end of the shaft is shown in Fig. 6. Figure 7 shows the air core current limiting reactor which is indicated on the diagram, Fig. 1.

Theory of Operation

When in the elementary explanation given above it is stated that a positive grid voltage makes the tube conducting and the negative voltage makes it nonconducting, this statement applying to present-day commercial tubes should be qualified: A positive voltage makes the tube conducting and a negative voltage prevents it from becoming conducting but it does not interrupt a current which has already been established.

The transfer of current from one tube to another is called commutation in analogy of transfer of current from one commutator segment to another. In a d-c motor with sparkless commutation the current is transferred from one segment to another by the electromotive forces in the windings acting between those 2 segments and not by the breaking of the contact between the brushes and the segment. This analogy between the d-c motor and the thyratron motor is accurate because the transfer of current takes place as a result of electromotive force in the motor winding. If these electromotive forces are not adequate to complete the commutation, there is a commutation failure which is analogous to the sparking of the commutator. It has been the ob-

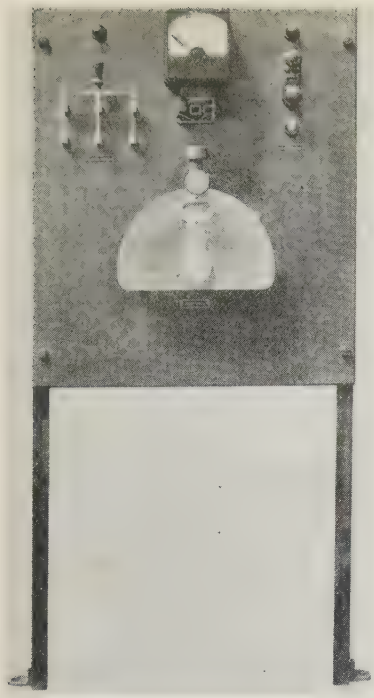


Fig. 5. Operating panel

arc-back serves as a cleaning process which removes from the anode accumulated contamination which was the cause of formation of a cathode spot and conductivity in the wrong direction. Thus, it may be observed that the arc-back not only did not damage the tube but on the contrary improved it. It is evident, however, that a failure of this sort illustrated by this oscillogram and a consequent shutdown is not permissible in practical operation. All electrical apparatus must somehow be protected from current so excessive compared with that for which it is designed. As a practical solution to this there was

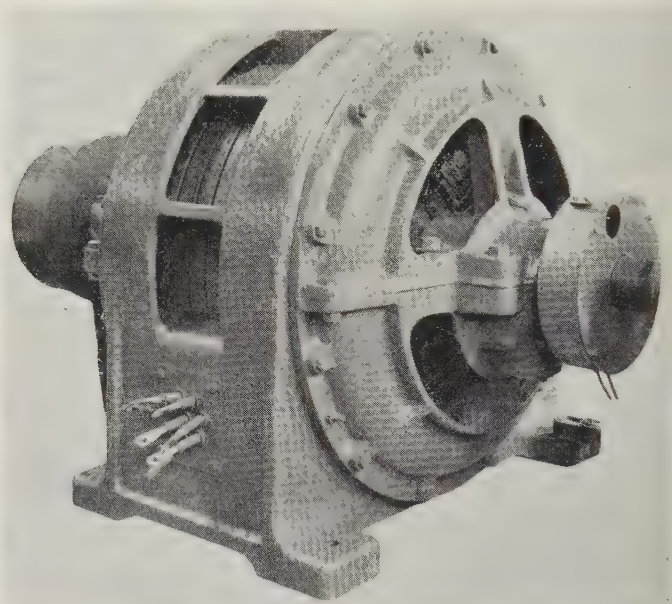


Fig. 6. The thyratron motor

ject of the present development work to establish methods for designing thyratron motors so that commutation failures do not occur in normal operation and if they do occur due to some abnormal circumstances, they are only of minor consequence and do not cause a shutdown of operation.

The principal sources of failure in a thyratron circuit can be classified as those originating in the power circuit, those originating in the grid circuit, and those originating within the tubes. The oscillogram reproduced in Fig. 8 illustrates a failure of a type which should not occur, and for which there have been found means to avoid. The oscillogram shows first an increase of current from the operating current to an abnormal value. This increase was due to a failure of grid control and may have originated within the tube or may have originated in the grid circuit by imperfect contact on the distributor. The excessive current caused by this commutation failure runs along for several cycles and then there appears a still more excessive current in a reverse direction which indicates a tube failure of the nature that is called arc-back, meaning that a tube conducts in the direction in which it should always be nonconducting. The arc-back, however, lasts only one-half cycle after which normal operation is resumed and the circuit breaker opens shortly afterward only because the tripping mechanism had been set in motion. The tube used in these tests had a continuous rating of 12.5 amp and a maximum rating of 75 amp, and it is therefore significant to know that the arc-back current shown in the oscillogram has a magnitude of 1,200 amps. Nevertheless, the tube was not damaged.

Another important observation may be made from this oscillogram. The arc-back current lasts only $^1/_2$ cycle, although the circuit was closed for several cycles before the circuit breaker opened. From this it has been concluded that the occurrence of the

introduced into the power supply a 3-phase reactor which limits the short-circuit current to 5 times normal; and the result of this change was that, while with the original arrangement arc-overs and shutdowns occurred about once a day, these failures have been entirely eliminated. It is possible and in fact probable that reversals of current which theoretically are called arc-backs still occur from time to time although they are of such limited intensity and such short duration that they are not discovered by ordinary instruments. If this theory is correct, contamination may gradually accumulate on the anode during normal operation until a momentary reversal of current takes place which removes the contamination. Future experience will show whether this interpretation is correct but at any rate arc-backs have been eliminated as a factor in practical operation. It should also be observed that while the arc-back is a failure which takes place within the tube the practical remedy has not been to change the tubes but to change the proportions of the power circuit.

Most of the failures recorded by the automatic oscillograph from which Fig. 8 was taken are indicated as failure of grid control without arc-backs. All such failures were eliminated by the use of the current limiting reactor. The difficulties encoun-

tered in earlier operation, in the form of arc-backs and grid failures, have thus been overcome. The remedy, however, was not a change in the design of the tubes but a change in the design of the power circuit. If the rules of design thus learned are observed the operation should be stable and reliable.

One evidence of the proper functioning of the commutation can be found by shifting the brushes on the distributor, just as the brushes of the d-c machine may be shifted to establish the point of best commutation. If the brushes are shifted in the direction of rotation a position will be found where the commutation begins to fail. The evidence of such incipient failures may be found by observing with an ammeter the current consumed by the motor, which becomes unsteady showing a succession of kicks tending toward higher current. The brushes may then be shifted again in the opposite direction until the current becomes steady. This method of adjustment is quite analogous to the adjustment of a d-c machine for sparkless commutation. It should be observed, however, that a brush shift against the direction of rotation does not result in commutation failure and is limited only by the operating characteristics because of the reduction of the counter electromotive force of the motor. The proper position of the brushes, therefore, gives a fair and safe margin from the point where commutation failures begin.

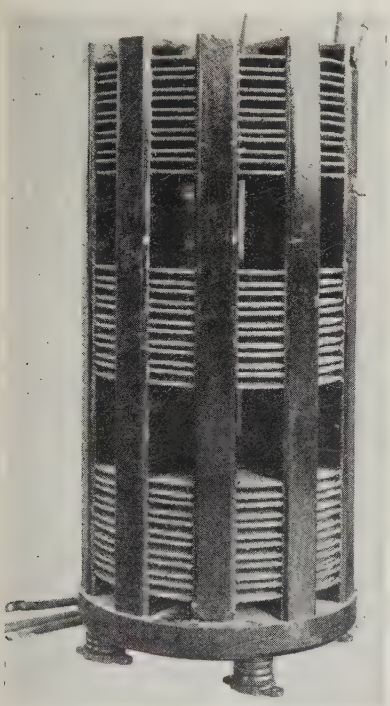


Fig. 7. Current limiting reactor used in connection with the thyratron motor

Two Kinds of Commutation

The discussion of the theory of commutation so far has referred to operation within the normal range of speed. It was shown that commutation takes place as a result of electromotive forces in the motor circuit. However, at starting and very low speeds there is insufficient electromotive force in the motor windings to cause commutation in accordance with the theory that has been given. This is one of the reasons for using the arrangement shown in Fig. 1, where the same tubes are used for rectification and commutation at the same time rather than the arrangement in Fig. 3, where separate tubes are used for rectification and commutation. The first arrangement provides commutation at standstill and low speeds whereas the second arrangement does not. The reason for this is that while commutation depending upon electromotive force in the motor circuit does not function at low speeds, each tube in the arrangement of Fig. 1 is associated with the power circuit as well as the motor circuit and, therefore, while the electromotive force in the motor circuit is absent, the commutation is caused by the electromotive force in the power circuit. Thus, there are 2 kinds of commutation, one caused by the electromotive forces in the motor circuit when used at full speed and the other caused by electromotive forces in the power circuit which are effective at standstill and low speeds. In the first case the commutation is initiated by the voltage of the grids and timed by the distributor. The timing of this commutation is, therefore, accurate and is controlled by the grid circuit. It may, therefore, be called grid commutation.

The other type of commutation which is effective at standstill and low speeds is not so accurately timed by the distributor. When the grid goes negative as the result of interruption of the distributor contact, this does not in itself cause any change in the power circuit. The current continues to flow as before until the electromotive force in the power circuit goes through zero and thus interrupts the current in one tube and transfers it to another tube which sometime earlier had been made conductive by the grid circuit. Thus it can be seen that it is

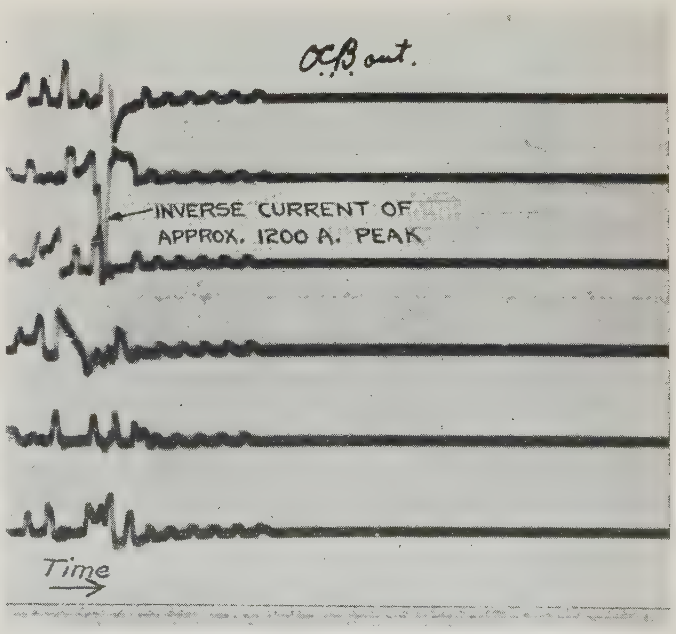


Fig. 8. Oscillogram showing control failure and arc-back

the voltage of the anode and not the voltage of the grid that determines the time when the commutation will take place. This may be called anode commutation. The anode commutation is fully effective at standstill but begins to lose its effectiveness at from $^1/_3$ to $^1/_2$ speed because of the inaccurate timing. Thus the motor starts with anode commutation which is as effective in producing starting torque as the commutator in any d-c motor. As the motor begins to gather speed and to acquire electromotive force, the grid commutation becomes effective and thus the motor continues to operate at full torque efficiency at all speeds between standstill and its highest speed. The arrangement in Fig. 1 by which each tube performs both rectification and commutation has thus the advantage that it has inherently 2 systems of commutation, both of which can function simultaneously although one is useful at low speed and the other more useful at high speed. Although the motor should function with grid commutation exclusively at high speed, there is some advantage in having the anode commutation, so to say, in reserve; because, if the grid commutation should fail momentarily, there is the anode commutation to fall back upon. This means that if some particular current transfer did not take place when properly timed by the grid, it would be forced to take place a fraction of a half cycle later by anode commutation. This makes operation as a whole more reliable and explains why only a slight disturbance is observable when the distributor brushes are adjusted so that the commutation begins to fail.

Operating Characteristics

The operating characteristics of the thyratron motor may be better compared with a steam engine than with any other electric motor. The phase shifter in the grid circuit which is used by the operator for starting the motor and adjusting the speed admits to the motor the current flow needed to produce the desired power and may appropriately be called a throttle control in analogy with the throttle on a steam engine. The resistance used for speed control of slip ring induction motors might also be called throttle control, but the throttling in the thyratron motor is accomplished by reduction of power factor instead of by wasting of energy. This has the double advantage that no provisions need to be made for dissipating wasted energy and that the wattless kilovoltamperes consumed at reduced speed by the thyratron motor are much cheaper than the corresponding kilowatts of the resistance control, and can be compensated at a comparatively low cost by the use of capacitors or synchronous condensers.

As may be seen from the diagram of Fig. 1, the motor field is excited by the direct current that results from the rectifier action of the tubes. It is also possible to operate the motor with a separately excited field but the series excitation has proved the most convenient and gives the high overload and starting torque characteristic of a series motor. In Fig. 9 is shown the speed-torque characteristics with the throttle control full open as well as with various settings for reduced power. In Figs. 10 and 11 are shown the adaptation of the thyratron motor to

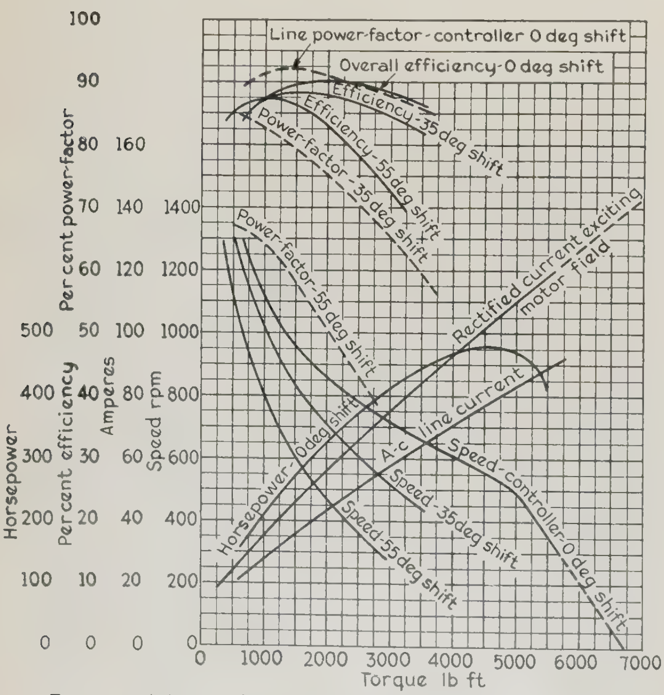


Fig. 9. Motor characteristics with different settings of the controller

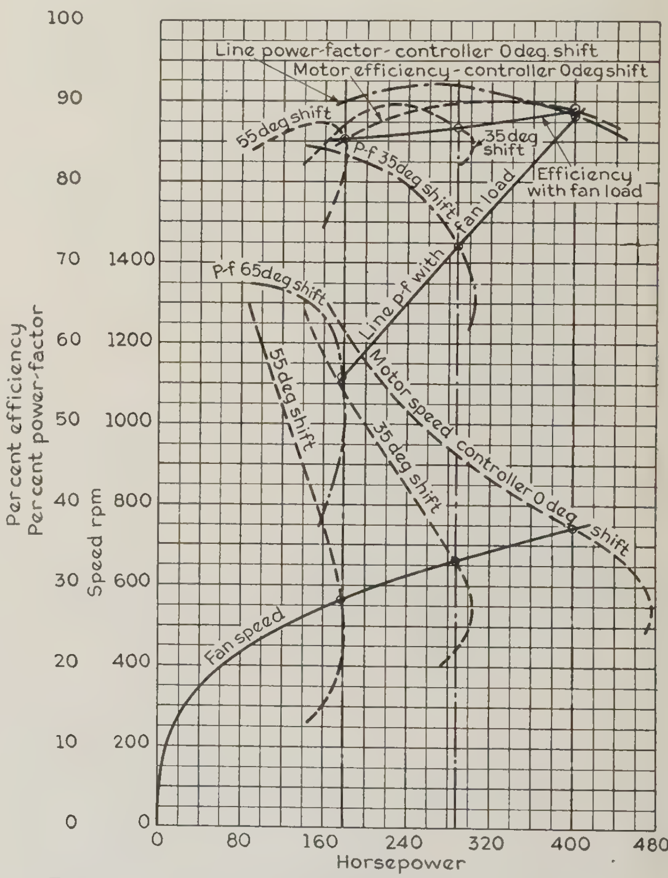


Fig. 10. Motor characteristics with variable speed control for fan load

drive a fan at variable speed. The speed-horsepower characteristics of the fan are superimposed upon the motor characteristics so that intersection points of the speed curves give the actual points of operation, and thus are constructed curves showing efficiency, power factor, kilowatts, and wattless kilovoltampere consumption of the motor at various operating speeds of the fan. Among the operating characteristics the wave shape of current drawn from the line should be mentioned. From the point of view of the power supply the thyratron motor is nothing but a 6-phase grid-controlled rectifier. Therefore the same considerations apply to the practice dealing with the wave shape of the thyratron motor as with such rectifiers.

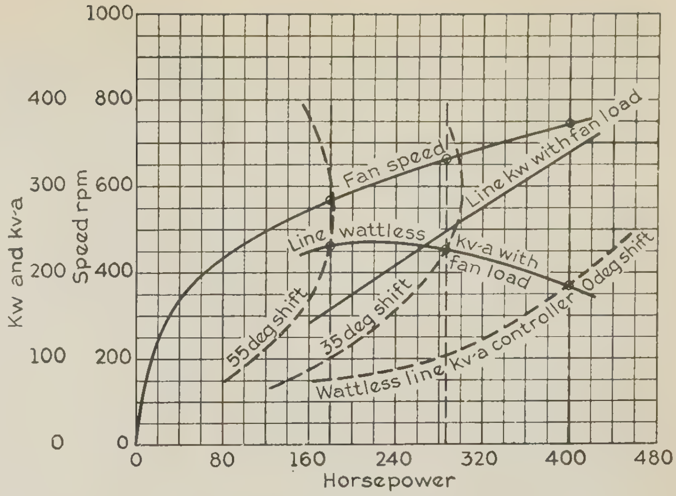


Fig. 11. Kilowatts and wattless kilovoltampere consumption with fan load

Automatic Control

The throttle control which is a function of the grid circuit lends itself well to automatic and remote control. One feature of automatic control which has been incorporated in the commercial motor design is of particular interest because of its effect upon reliability and continuity of operation. Up to full power of the motor of 400 hp the throttle remains wide open when set in the "full on" position, but if the load is increased so that the motor draws more than full load current from the line, this current reacts upon the grid circuit in such a way as to modify the phase displacement of the grid voltage independently of the phase determined by the position of the controller. The effect of this reaction of the line current upon the grid control is to limit the current which the motor can draw from the line. This automatic current limiting control has been worked out in such a way that the motor may be started from standstill with the throttle control wide open without drawing any more overload current from the line than that for which the apparatus is adapted and less than that for which the automatic circuit breaker is adjusted. The starting of the motor may thus be made entirely automatic from a remote point if desired and the arrangement insures continuity of operation with less attention. The controller may thus remain in the operating position at either full or fractional speed, and the motor may be started by remote control of the main circuit breaker and will immediately come up to its normal operating speed.

Reliability

The reliability in the functioning of the thyratron motor which has been aimed at and attained may be characterized by saying that it has stability of commutation. If a momentary commutation failure results in further accumulative changes of the functioning of the system and results in a short circuit, the commutation is unstable. When, on the other hand, such proportions of design have been observed that stable commutation has been established it should be possible to disturb this normal operation momentarily in almost any way whatever and normal operation should resume itself immediately when the cause of the disturbances has been removed. The stability of commutation may be tested by purposely introducing such disturbances as open circuiting the power supply, interruption of the grid circuit, or misadjustments of the brushes on the distributor. Whatever disturbance is chosen as a test of stability of operation, normal operation should be resumed as soon as the circuit is reëstablished.

If any one tube is removed from the circuit the current will be carried by the adjacent tubes and operation is possible at reduced load. The current flow in any one tube may be interrupted during operation by disconnecting the grid circuit and such a measure may be used as a preliminary step to remove the tube if it should prove to be defective. It is still too early to forecast what routine of inspection and tube replacement should be put into effect for maintenance of this type of motor. It is probable that some practice will be established similar to maintenance of brushes on the commutator which also have a limited life. Ways may be thought of for taking a tube out of the circuit automatically by short circuiting or disconnecting the grid if the tube has been carrying excessive current for a prolonged period. It has not, however, been attempted to introduce such automatic devices in the first commercial design because simplicity is of greater value than automatic features in a new device which must necessarily receive some more attention by the operators.

As has already been pointed out, the thyratron equipment may be subjected to a great many disturbances without interruption of service. Fluctuations of the voltage of the power supply such as may be found in commercial systems will not cause any disturbance of operation but will only modify the speed-torque characteristic as with a d-c motor. Similarly, unbalancing of the voltage does not disturb operation; in fact one phase may be disconnected entirely and the motor will run on single-phase power supply with reduced load. The power flow through the thyratron set is irreversible and therefore a short circuit on the power system will not tend to stop the motor. If, on the other hand, it is desired to use the motor as an electric brake it is possible to so arrange the control that power will flow from the motor back into the line.

Discussions

Of A.I.E.E. Papers—as Recommended for Publication by Technical Committees

ON THIS and the following 17 pages appear discussions of papers presented at the 1934 A.I.E.E. summer convention, Hot Springs, Va., June 25–29, as follows: (1) one paper presented at the session on electrical machinery (closure); (2) one paper presented at the session on power generation; (3) all papers presented at the session on automatic stations; and (4) all papers presented at the session on insulators. All discussions on the foregoing papers (except that in item No. 1) received in complete and acceptable form at Institute headquarters, and subsequently reviewed and recommended for publication by A.I.E.E. technical committees, are included. Authors' closures, where they have been submitted, will be found at the ends of the discussion on their respective papers.

Members anywhere are encouraged to submit written discussion of any paper published in Electrical Engineering, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions on papers scheduled for presentation at an A.I.E.E. meeting or convention will be closed 2 weeks after presentation. Discussions should be (1) concise; (2) restricted to the subject of the paper or papers under consideration; and (3) typewritten and submitted in triplicate to C. S. Rich, secretary, technical program committee, A.I.E.E. headquarters, 33 West 39th Street, New York, N. Y.

Insulation Resistance of Armature Windings

Author's closing discussion of a paper published in the June 1934 issue, p. 1010–21, and presented for oral discussion at the electrical machinery session of the summer convention, Hot Springs, Va., June 27, 1934. Other discussions of this paper were published in the October 1934 issue, p. 1407–11.

R. W. Wieseman: Mr. Rutan states that the formulas proposed in the paper give a minimum insulation resistance (condition 4, Table I) which is too low for synchronous converters. The resistance for condition 4 is based on a winding temperature of 75 deg C, so this value of resistance is low if the winding is measured at room temperature.

It is recognized that many operators will not allow the insulation resistances of their machines to fall to a value given for condition 4. This is the minimum value and favorable operating conditions will maintain the resistance above this minimum value. For the reasons which Mr. Rutan pointed out, coefficients for condition 3 were incorporated in Table I of the paper. It is suggested, therefore, that Mr. Rutan consider condition 3 the bench mark value of insulation resistances of machines in good condition.

Messrs. Henderson and Calvert called attention to the absence of test data in Tables II, III, and IV. These tables show a comparison of minimum insulation resistance values obtained by existing formulas and by the formulas recommended in the paper. The machine ratings listed in the tables are hypothetical and test data on these machines, therefore, are not available. Tests on many machines, however, were used to evaluate and check the coefficients of the new formulas.

In the test data submitted by Messrs. Henderson and Calvert, some machines had resistance values below that of the American Standards Association formula and the formulas recommended in the paper. The A.S.A. formula applies only when the winding is at a temperature of 75 deg C; consequently, all new machines will meet the A.S.A. values at room temperature. At 75 deg C, however, 5.9 per cent of the induction motors did not meet the A.S.A. values. These tests also bring out a very interesting point; namely, that the A.S.A. formula penalizes high voltage machines. In the formulas given in the paper this is not the case because the voltage of a machine is increased by a coefficient which places all machines regardless of voltage on the same basis. In other words, a formula based on machine dimensions is naturally more logical and more dependable than a formula which considers only the voltage and kilovolt-amperes of the machine.

Mr. Creagmile suggests that the ballast resistance of a megger should be shunted during the first few seconds of voltage application. This is a step in the right direction, especially for new machines where the absorption effect is very pronounced. Since much of the uncertainty of insulation resistance lies in the method of measuring the resistance, it is very desirable to eliminate as many variables as practicable and apply the full voltage instantly instead of allowing it to build up at a variable rate depending upon the electrostatic capacity of the winding.

The "one megohm standard" mentioned by Mr. Creagmile may apply by chance to certain groups of machines, but it cannot apply to all machines. Any "standard" of this kind is basically wrong and misleading and it should therefore be discouraged.

Mr. Hellmund points out that for many years insulation resistances were so irregular that they did not seem to be of real practical value. This is true in many cases because of the inconsistencies in the insulation resistance measurement itself. The paper emphasizes the point that consistent readings can be obtained only when the test is made under the same conditions; for example, after a 500-volt application for 1 minute. If this is done, some of the irregularities disappear.

Mr. Hellmund questions the amount of variation in the coefficients of Table I. These variations are caused by the effect of temperature, moisture, and other foreign matter in the insulation and can readily be checked by test. It is admitted that the insulation resistance of a winding is determined more by foreign matter in or around the winding than the machine dimensions. This large variation caused by impurities is taken into account by the new formulas and apparently this is just what the operators have desired for many years. Thus the paper gives for the first time expressions for the insulation resistance of an armature winding when a machine is new and when a machine has had favorable operating conditions, and also the minimum insulation resistance which indicates when a winding should be carefully inspected and reconditioned if necessary.

The author does not agree with Mr. Rylander that the formulas (accompanied by nomograms) given in the paper are complicated and that they are less accurate than the present formulas. A simple expression, which includes only the voltage of the machine and an experience factor, cannot be so accurate and dependable as an expression based on actual machine dimensions and governed by test values of insulation resistivity.

Mr. Rylander states that the suggested formulas do not eliminate any of the major variables: temperature, moisture or solvent content, and foreign matter. Table I clearly indicates the winding temperature to which the coefficients apply. The formulas cannot indicate the amount of moisture, solvent, foreign matter, or mechanical damage, etc., of the insulation. These variables are complex, but their combined effect on the winding is to lower its insulation resistance. The suggested formulas (condition 4), therefore, give a minimum value which is a red flag to stop the unfavorable action of 1, 2, or all of these variables. With reference to the lack of confidence in the coefficients of Table I and their large variation, this is simply a matter of obtaining the necessary test data. It is recognized that mica insulation compound-filled under vacuum (class B) is much more resistant to moisture and foreign material than varnished fabric (class A) insulation. Thus mica insulated machines in service have a higher resistance than varnished fabric insulated machines. Furthermore, as stated in the paper, mica insulated machines are usually important machines and they should be maintained at a relatively higher insulation resistance.

In regard to the difficulty of choosing the resistivity coefficient for mixed insulation, this again is simply a matter of obtaining

test results on this type of insulation. With reference to the lack of consistent relationship among the various "constants" in Table I, Mr. Rylander is referred to p. 6 of the paper, which explains that all constants were incorporated in the coefficient k for simplicity. The fact that different machines have different values of k for the same class of insulation, therefore, does not prove that the insulation resistivity of these machines is necessarily different or that the insulation of one type of machine is superior to that of another.

Mr. Rylander states that foreign matter may change the resistance values 10 times or 100 times or in some cases even 1,000 times. Figure 8 in the paper shows that Class A insulation resistivity can change 100,000,000 times by allowing it to absorb moisture for a long time.

Mr. Rylander's test data, Fig. 1, show the manner in which insulation resistance changes with temperature, moisture, and solvent on a particular line of induction motors. It is an odd coincidence that at 75 deg C the machines which were allowed to absorb moisture should have a resistance of exactly 1 megohm, the value proposed by some as the minimum insulation resistance for any machine.

With reference to Mr. Reed's criticism of item 11, p. 1010, it is obvious that other things besides moisture lower insulation resistance. This paragraph deals only with the effect of moisture on insulation resistance just as items 3, 4, and 5 describe only the effects of temperature, applied voltage, and time of voltage application, respectively. Mr. Reed objects to the numerous formulas, one for each type of machine, the different coefficients for each class of insulation and type of machines and the "arbitrary" nature of these coefficients, and to the special consideration given to single phase machines, etc. These factors must all be taken into consideration in determining a bench mark value of the insulation resistance of an armature winding. Conversely, the lack of appreciation of these factors is one reason why insulation resistance has been considered so erratic for many years.

Mr. Reed states that during the past 12 years more than 750,000 insulation resistance readings were taken on all kinds of electrical apparatus and that insurance is withheld if the resistance is less than 1 megohm per 1,000 volts. Incidentally, we know of a number of machines which have given reliable service with insulation resistances less than that prescribed by Mr. Reed. Insurance is based on averages so that what one gains by insurance another must lose. The paper is a step forward in this respect because it is not based on averages and "more or less" definite indications. It does not handicap one machine and benefit another, but it evaluates each machine on its own merits based on the machine dimensions and insulation characteristics.

In conclusion, it is emphasized that the formulas for insulation resistance derived in the paper are based first on the machine dimensions and second on resistivity tests which include the characteristics of the insulation. Thus these formulas are on a rational basis and they, therefore, should supersede all rule of thumb expressions such as 1 megohm per 1,000 volts. Furthermore, the paper calls attention to the fact that many of the erratic features of insulation resistance readings in the past were caused by the inconsistent methods of measuring insulation resistance. The formulas given in the paper enable one to obtain, for reference, the insulation resistance of the machine when new. In fact, the formulas can be used to check the quality of the insulation and the effectiveness of the insulation treatment. It is hoped that operating engineers will also obtain data on machines in service and thereby aid in evaluating more closely the coefficients for conditions 3 and 4, Table I.

Voltage Regulation and Load Control

Discussion and author's closure of a paper by H. C. Forbes and H. R. Searing published in the June 1934 issue, p. 903–9, and presented for oral discussion at the power generation session of the summer convention, Hot Springs, Va., June 29, 1934.

F. M. Starr: The authors have demonstrated clearly the improvement in system operation which can be obtained by making a thorough study and by the utilization of accurate and suitable instruments. It is of particular interest to note the excellent results which have been obtained in controlling load and phase angle by the methods described. Figures 6, 10, and 12 in the paper offer ample evidence of the benefits obtained.

Perhaps it should be pointed out that the problems which have been treated here are rather special ones, considering power distribution systems in general. In few cases—outside the New York area—is a secondary network fed by more than one generating source. In fact, the large majority of secondary networks in this country are fed from single bus.

In a few cases a small network may be fed by 3 or 4 feeders, each from a separate substation bus. In these cases the respective buses are usually firmly tied together with cable ties. During certain emergency operating conditions, these ties may carry considerable load, but the phase angle difference between 2 buses is scarcely ever more than 1 deg. Since networks of this type are usually small, the circulating impedance between buses and through the network is high, and as a result very little power is circulated. Moreover, the maximum phase angle difference will usually occur during the time of peak network load when even a large circulating power current will not be sufficient to give a net power reversal in any network protector.

Therefore, in general, the severe operating conditions in the New York area and the problems arising therefrom are not met in the average network distribution system. Nevertheless, the methods of control which Messrs. Searing and Forbes have developed should be of considerable general interest. The excellent results which have been obtained should stimulate study and activity along these lines by other operating engineers.

The load control scheme shown in Figure 11 and described briefly in the paper is of particular interest. I should like to ask the authors to explain in more detail exactly how the regulators and compensator function. Offhand this arrangement would appear to function in such a manner as to circulate a fairly large component of negative phase current. However, this condition may not be serious. This particular scheme is certainly a novel one and more complete operating data on the results obtained would be of considerable interest.

A. H. Sweetnam: The relative values of the load and reactive currents through the network units and in the tie lines between the generating stations is a problem of long standing in a new setting. We have long been accustomed to adding paralleling reactors to cables or transformers operating in parallel with units of different characteristics, but as a word of caution it should be kept in mind that there have probably been many instances where the desire for mathematically correct division has exceeded the economic justification. This paralleling problem at New York is considerably complicated by the nature of the circuits involved, the tapped loads, the necessity of variable load transfers, the voltage requirements at various parts of the system, etc., and the New York engineers are to be congratulated on their ingenuity and skill in arriving at a successful solution.

On a system as large as that in New York the conditions warrant such major operations as the design of new and supersensitive voltage and phase angle recording and remote indicating instruments, and the installation of voltage and load ratio transformer units in the paralleling tie lines.

In most cases, however, the network installation is only a small part of the system and the voltage or load angle relationships of the various generating stations or bus sections are determined by the requirements of the rest of the system. For example, the Boston Edison Company has the bulk of its distribution through radial substations and any interconnections between stations or with other companies as affecting bus voltages and angles are based on load requirements, feeder capacities, reserve generating capacity, relative station efficiencies, etc.

Even with the carefully controlled system at New York there will still be many cases of tripping of the network units due to reverse currents caused by certain types of regenerative loads, switching surges and unbalanced conditions when several high tension feeders are open. Also if one feeder supplies several different network areas, theoretically at least, it cannot be entirely compensated for by station control.

All of this leads to the necessity of further development at the network unit itself. There have been some changes recently in the relaying, such as by the addition of negative sequence control, but this is not the final answer.

Further study should be made of the effect on the reactive current division caused by operation of the voltage tap changers on the network transformers. These may be controlled or biased by some other method of load compensation or possibly recalibrated by time switches or remote control. This applies principally to the primary units which already have tap chang-

ing under load equipment, but some form of simple tap changer could be developed for the secondary units if found justifiable. In some cases it might even pay to include a few taps of the transformer arranged for load ratio control as well as for voltage variation.

There may be cases where reactors, separate regulators, or booster transformers could be justified in the high tension or secondary circuits, to aid in proper current control. It is thought, however, that it would be preferable to eliminate the need for all of these complications by supplying each network area from one source. The present ruggedness in design and reliability of operation for generating stations justifies the growing tendency to reduce duplication of apparatus. The various feeders supplying the area could be taken from one bus which could be sectionalized automatically in case of a bus fault, the feeders affected being transferred to an auxiliary bus. Experience shows that the remaining feeders and transformers during this transition period could well handle the temporary overload conditions. This single source idea might not always be suitable for primary network installations, but for the general secondary area it should be applicable.

Giuseppe Calabrese: The paper by Messrs. Forbes and Searing describes 2 methods for transferring power between 2 stations, shown respectively in Figs. 7 and 8 of the paper. In Fig. 7, a voltage at 120 deg with the phase voltage is injected in each phase. With the 2 station voltages equal in phase and magnitude, the power factor at which power can be exchanged is entirely determined by the impedance of the tie line, excepting for the effect of the drop between the bus and the point where the regulating transformer shunt winding is connected, a factor which is quite negligible. The series voltage necessary to transfer a predetermined amount of power can be calculated by noting that the same voltage is consumed by the drop in the tie line.

In the scheme of Fig. 11 of the paper, only 2 induction regulators are used. However, neglecting the effect of the regulator and potential transformer magnetizing currents and leakage impedances, as far as the transfer of power is concerned, the scheme of Fig. 11 is equivalent to the scheme of Fig. 7, that is, the transfer of power takes place as if a series voltage at 120 deg were injected in each phase exactly in the same manner as in Fig. 7. As this equivalence may not be apparent to all, I believe it will be of interest to prove it. Referring to Fig. 1 of this discussion, let $\boldsymbol{E}_a$, $\boldsymbol{E}_b$, and $\boldsymbol{E}_c$ be the line to neutral voltages at the terminals a b, and c of the regulator shunt windings. (Bold faced letter symbols indicate vector quantities; others indicate scalar quantities.) Similarly, $\boldsymbol{E}_a'$, $\boldsymbol{E}_b'$, and $\boldsymbol{E}_c'$ are the voltages from a', b', and c' to ground. If K is the regulator ratio in any particular position, from Fig. 1, showing the regulators in the boosting position, there is obtained

$$\begin{aligned} \boldsymbol{E}_a' &= \boldsymbol{E}_a - K(\boldsymbol{E}_b - \boldsymbol{E}_c) \\ \boldsymbol{E}_b' &= \boldsymbol{E}_b \\ \boldsymbol{E}_c' &= \boldsymbol{E}_a + K(\boldsymbol{E}_c - \boldsymbol{E}_a) \end{aligned}$$

Let $\boldsymbol{E}_0'$ $\boldsymbol{E}_1'$ $\boldsymbol{E}_2'$ be the sequence components of the 3 voltages $\boldsymbol{E}_a'$, $\boldsymbol{E}_b'$, $\boldsymbol{E}_c'$ and $\boldsymbol{E}_0$, $\boldsymbol{E}_1$, $\boldsymbol{E}_2$ the sequence components of the 3 voltages $\boldsymbol{E}_a$, $\boldsymbol{E}_b$, $\boldsymbol{E}_c$. It is obtained

$$\begin{aligned} \boldsymbol{E}_0' &= \boldsymbol{E}_0 + K(a\boldsymbol{E}_1 + a^2\boldsymbol{E}_2) \\ \boldsymbol{E}_1' &= \boldsymbol{E}_1 - Ka^2\boldsymbol{E}_1 \\ \boldsymbol{E}_2' &= \boldsymbol{E}_2 - Ka\boldsymbol{E}_2 \end{aligned}$$

in which a and a^2 are the well-known operators indicating rotations of 120 and 240 deg, respectively. As generators generate voltages of positive sequences only, and normally there are no unbalanced loads or faults on the system,

$$\boldsymbol{E}_2' = \boldsymbol{E}_2 = 0$$

The expression of $\boldsymbol{E}_0'$ shows that the 2 regulators generate zero sequence voltage. As the normal operation of the Hell Gate station is with one generator on each bus section grounded, it becomes necessary to operate the Sherman Creek generators ungrounded in order to prevent the flow of zero sequence current. With Sherman Creek ungrounded and no unbalanced loads or faults on the system, $\boldsymbol{E}_0$ becomes zero. Thus during normal operating conditions, the sequence components of the voltages at the regulator terminals are:

$$\begin{aligned} \boldsymbol{E}_0 &= \boldsymbol{E}_2' = \boldsymbol{E}_2 = 0 \\ \boldsymbol{E}_0' &= Ka\boldsymbol{E}_1 \\ \boldsymbol{E}_1' &= \boldsymbol{E}_1(1 - Ka^2) \end{aligned} \tag{1}$$

The second of these equations shows that the regulators, in acting as source of zero sequence voltage, shift the neutral on the Sherman Creek side by the voltage $Ka\boldsymbol{E}_1$. However, as said, with the Sherman Creek generators ungrounded, this zero sequence voltage cannot force the flow of zero sequence currents excepting through parallel feeders if an equal and opposite amount of zero sequence voltage is not injected in the latter. During fault conditions, the zero sequence voltage generated by the regulators will force zero sequence current in both the parallel lines and through the fault. This point should be kept in mind in setting relays, especially if there is the possibility that regulators on parallel feeders may take different positions.

Equation 1, however, shows that as far as the positive sequence voltages are concerned, that is, the voltages that cause the exchange of power, the scheme of Fig. 1 is equivalent to injecting in each phase a voltage $-Ka^2\boldsymbol{E}_1$ (at 120 deg with the phase voltage), exactly in the same manner as in the case of Fig. 7 of the paper. Thus, the same method of calculation may be used to determine the series voltage necessary to establish a predetermined exchange of power.

Regarding the automatic control of the power exchanged between 2 stations with the scheme of Fig. 11, it may be of some interest to analyze under which conditions automatic operation is possible and to show how to calculate the setting of the line drop compensator.

By automatic operation is meant operation whereby, starting with the 2 station voltages equal in phase and magnitude, any variation of load at either station will cause the regulators to transfer power in such amount and direction that the 2 station voltages are maintained equal in phase and magnitude. All the voltages acting in the circuit of the primary relay during normal conditions, that is, with no unbalanced loads or faults on the system are shown in Fig. 1.

$\boldsymbol{E}_{Ha}$, $\boldsymbol{E}_{Hb}$, and $\boldsymbol{E}_{Hc}$ are the Hell Gate line to ground voltages, and $\boldsymbol{E}_{H0}$, $\boldsymbol{E}_{H1}$, and $\boldsymbol{E}_{H2}$ their sequence components. During normal conditions, $\boldsymbol{E}_{H0} = \boldsymbol{E}_{H2} = 0$, that is, $\boldsymbol{E}_{Ha} = \boldsymbol{E}_{H1}$; $\boldsymbol{E}_{Hb} = a^2\boldsymbol{E}_{H1}$; $\boldsymbol{E}_{Hc} = a\boldsymbol{E}_{H1}$.

$\boldsymbol{E}_{Sa}$, $\boldsymbol{E}_{Sb}$, and $\boldsymbol{E}_{Sc}$ are the corresponding Sherman Creek voltages, and $\boldsymbol{E}_{S0}$, $\boldsymbol{E}_{S1}$, and $\boldsymbol{E}_{S2}$ their sequence components. Normally, $\boldsymbol{E}_{S2} = 0$, that is, $\boldsymbol{E}_{Sa} = \boldsymbol{E}_{S0} + \boldsymbol{E}_{S1}$; $\boldsymbol{E}_{Sb} = \boldsymbol{E}_{S0} + a^2\boldsymbol{E}_{S1}$; $\boldsymbol{E}_{Sc} = \boldsymbol{E}_{S0} + a\boldsymbol{E}_{S1}$.

The relations between the voltages at a, b, c and a', b', c' have been given already.

The following analysis is made assuming the regulators in the boosting position. However, the results obtained may be extended to the bucking position by changing the sign of the factor K.

Let $\boldsymbol{I}_a$, $\boldsymbol{I}_b$, and $\boldsymbol{I}_c$ be the currents out at Hell Gate, and $\boldsymbol{I}_0$, $\boldsymbol{I}_1$, and $\boldsymbol{I}_2$ their sequence components. Let $\boldsymbol{I}_a'$, $\boldsymbol{I}_b'$, and $\boldsymbol{I}_c'$ be the corresponding currents in at Sherman Creek, and $\boldsymbol{I}_0'$, $\boldsymbol{I}_1'$, and $\boldsymbol{I}_2'$ their sequence components.

Neglecting the magnetizing currents of the regulators and potential transformers, from Fig. 1 is obtained

$$\begin{aligned} \boldsymbol{I}_a &= \boldsymbol{I}_a' - K\boldsymbol{I}_c' \\ \boldsymbol{I}_b &= \boldsymbol{I}_b' - K\boldsymbol{I}_a' \\ \boldsymbol{I}_c &= \boldsymbol{I}_c' + K(\boldsymbol{I}_a' + \boldsymbol{I}_c') \end{aligned}$$

From which

$$\begin{aligned} \boldsymbol{I}_0 &= \boldsymbol{I}_0' \\ \boldsymbol{I}_1 &= \boldsymbol{I}_1' + K(a^2\boldsymbol{I}_0' - a\boldsymbol{I}_1') \\ \boldsymbol{I}_2 &= \boldsymbol{I}_2' + K(a\boldsymbol{I}_0' - a^2\boldsymbol{I}_2') \end{aligned}$$

During normal conditions, $\boldsymbol{I}_0 = \boldsymbol{I}_0' = \boldsymbol{I}_2 = \boldsymbol{I}_2' = 0$.

Thus:

$$\boldsymbol{I}_1 = \boldsymbol{I}_1'(1 - Ka) \tag{2}$$

Let θ be the angle by which the Hell Gate voltage $\boldsymbol{E}_{H1}$ leads the Sherman Creek voltage $\boldsymbol{E}_{S1}$ and assume that both have the same magnitude, that is, $E_{H1} = E_{S1}$.

The voltage difference between Hell Gate and Sherman Creek, as shown by the insert in Fig. 1, is:

$$j\,2\sin\frac{\theta}{2}\,e^{-j\frac{\theta}{2}}\,\boldsymbol{E}_{H1}$$

where $e^{-j\frac{\theta}{2}}$ is the well-known operator indicating a rotation in the negative direction of an angle $\frac{\theta}{2}$.

The series positive sequence voltage induced by the regulators is $-Ka^2\boldsymbol{E}_1$

Thus the total positive sequence voltage acting on the tie is

$$j\,2\sin\frac{\theta}{2}\,e^{-j\frac{\theta}{2}}\boldsymbol{E}_{H1} - Ka^2\boldsymbol{E}_1$$

This voltage must balance the drop due to the currents $\boldsymbol{I}_1'$ and $\boldsymbol{I}_1$ flowing respectively through the impedances $\boldsymbol{Z}$ and $\boldsymbol{Z}_r$, that is,

$$j\,2\sin\frac{\theta}{2}\,e^{-j\frac{\theta}{2}}\boldsymbol{E}_{H1} - Ka^2\boldsymbol{E}_1 = \boldsymbol{I}_1'\boldsymbol{Z} + \boldsymbol{I}_1\boldsymbol{Z}_r$$

Substituting for $\boldsymbol{I}_1$ the value given by eq 2 and for $\boldsymbol{E}_1$ the value given by

$$\boldsymbol{E}_1 = \boldsymbol{E}_{H1} - \boldsymbol{I}_1\boldsymbol{Z}_r \tag{3}$$

it is obtained that

$$\boldsymbol{I}' = \frac{\left(j\,2\sin\frac{\theta}{2}\,e^{-j\frac{\theta}{2}} - Ka^2\right)\boldsymbol{E}_{H1}}{\boldsymbol{Z} + \boldsymbol{Z}_r(1 + K + K^2)} \tag{4}$$

With the 2 station voltages in phase and the voltage regulators in the neutral

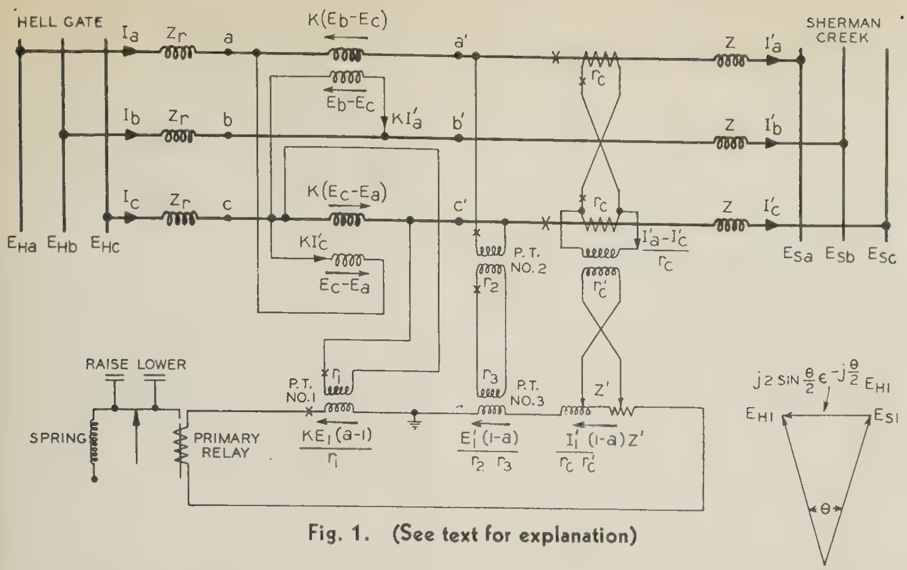


Fig. 1. (See text for explanation)

Z = impedance of line between regulators and Sherman Creek station
Z_r = impedance of line between regulators and Hell Gate station
r_1, r_2, r_3 = ratios of potential transformers (P.T.)
r_c, r_c' = ratios of current transformers
Z' = impedance of line drop compensator
All symbols indicate vectorial quantities

position, no current flows in the tie. The voltage impressed on the circuit of the primary relay is $\frac{\sqrt{3}\,E_{H1}\,e^{-j30°}}{r_2r_3}$. The pull on the relay is just enough to balance the tension of the spring. Both the raise and lower contacts remain open. Let us now add load at Sherman Creek. Sherman Creek will slow down, and current will flow through the tie causing a corresponding voltage to appear across the line drop compensator. The equilibrium between the spring tension and the primary relay pull is upset, and the latter overcomes the former, thus causing the raise contacts to close. The regulators start to boost the voltages at a', b', and c'. Additional voltages will be injected in the circuit of the primary relay through the transformers Nos. 1, 2, and 3, which, by balancing the voltage drop in the line drop compensator, are to cause the equilibrium between the spring tension and the primary relay pull to be restored (thus stopping the regulators) as soon as transfer of power in the proper amount necessary to bring the 2 station voltages in phase has been established. This is equivalent to saying that the condition of equilibrium will be restored and the regulators come to a stop when the resultant voltage acting in the circuit of the primary relay becomes equal to $\frac{\sqrt{3}\,E_{H1}\,e^{-j30°}}{r_2r_3}$. In a more general way, noting that the primary relay responds to the magnitude of the voltage impressed across it, the equilibrium is restored when the magnitude of the voltage acting in the circuit of the primary relay becomes equal to $\frac{\sqrt{3}E_{H1}}{r_2r_3}$. Thus automatic operation is possible if the line drop compensator impedance Z' is set to such a value that when transfer of power of the amount necessary to bring the 2 station voltages again in phase has been established, the magnitude of the resultant voltage acting in the circuit of the primary relay becomes $\frac{\sqrt{3}E_{H1}}{r_2r_3}$ (exactly or at least within such limits as may be set by the sensitiveness of the primary relay itself), regardless of the position of the regulators.

At any particular instant during normal operation, the line currents I_1' and aI_1' flowing in phases a' and c' at Sherman Creek cause a current $\frac{I_1'(1-a)}{r_cr_c'}$ to appear at the terminals of the line drop compensator. The current I_1' for any given angle between Hell Gate and Sherman Creek and any given position of the regulators is given by eq 4.

In the circuit of the primary relay, there act the following voltages:

The voltage due to potential transformer No. 1, $\frac{KE_1\,(a-1)}{r_1}$; or substituting eqs 3 and 4,

$$-\frac{\sqrt{3}Ke^{-j30°}}{r_1}E_{H1}\left\{\frac{Z+Z_r(1-Ka)\left(1-j2\sin\frac{\theta}{2}\,e^{-j\frac{\theta}{2}}\right)}{Z+Z_r\,(1+K+K^2)}\right\} \quad (5)$$

The voltage due to potential transformers Nos. 2 and 3, $\frac{E_1'\,(1-a)}{r_2r_3}$; or from eqs 1, 3, and 4,

$$\frac{\sqrt{3}\,e^{-j30°}}{r_2r_3}\,(1-Ka^2)E_{H1}\left\{\frac{Z+Z_r(1-Ka)\left(1-j2\sin\frac{\theta}{2}\,e^{-j\frac{\theta}{2}}\right)}{Z+Z_r(1+K+K^2)}\right\} \quad (6)$$

The voltage produced by the flow of the current $\frac{I_1'\,(1-a)}{r_cr_c'}$ through the impedance Z' of the line drop compensator, that is, from eq 4,

$$\frac{I_1'(1-a)Z'}{r_1r_2'} = \frac{\sqrt{3}e^{-j30°}}{r_cr_c'}\,E_{H1}\,\frac{\left(j2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}-Ka^2\right)}{Z+Z_r\,(1+K+K^2)}\,Z' \quad (7)$$

More accurately, Z' should be the parallel impedance of the line drop compensator and primary relay. In general, however, the effect of the latter may be neglected and Z' taken equal to the former.

The total voltage acting in the circuit of the primary relay is the sum of eqs 5, 6, and 7, that is,

$$\sqrt{3}\,E_{H1}\,e^{-j30°}\left[\left(\frac{1-Ka^2}{r_2r_3}-\frac{K}{r_1}\right)\left\{\frac{Z+Z_r\,(1-Ka)\left(1-j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}\right)}{Z+Z_r\,(1+K+K^2)}\right\}+\frac{\left(j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}-Ka^2\right)Z'}{r_cr_c'\{Z+Z_r(1+K+K^2)\}}\right] \quad (8)$$

From the previous analysis, it follows that the settings of the line drop compensator must be calculated by equating the difference between eq 8 and $\frac{\sqrt{3}E_{H1}\,e^{-j30°}}{r_2r_3}$ to zero or to $\frac{\sqrt{3}\,E_{H1}\,e^{-j30°}\,e^{\pm j120°}}{r_2r_3}$. Automatic operation is possible for those values of Z' thus obtained which are independent from the position of the regulators, that is, from the factor K.

By equating the difference to zero is obtained

$$\left(\frac{1-Ka^2}{r_2r_3}-\frac{K}{r_1}\right)\left\{\frac{Z+Z_r\,(1-Ka)\left(1-j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}\right)}{Z+Z_r\,(1+K+K^2)}\right\}-\frac{1}{r_2r_3}+Z'\frac{\left(j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}-Ka^2\right)}{r_cr_c'\,(Z+Z_r\,\{1+K+K^2\})}=0$$

From which the value of the impedance of the line drop compensator is

$$Z'=\frac{r_cr_c'}{2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}-Ka^2}\left\{Z_r\,(1-Ka)\,j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}\left(\frac{1-Ka^2}{r_2r_3}-\frac{K}{r_1}\right)+ZK\left(\frac{a^2}{r_2r_3}+\frac{1}{r_1}\right)+\frac{Z_r(1-Ka)K}{r_1}\right\} \quad (9)$$

This expression shows the value of Z' necessary to reach a position of equilibrium depends on both the position of the regulators and the angle between the 2 stations. In the particular case under consideration, it is desired that equilibrium be reached when the angle between the 2 stations becomes zero. The value of Z', in this case, as obtained from eq 9 by putting $\theta = 0$ is

$$Z'=-\frac{r_cr_c'}{a^2}\left\{Z\left(\frac{a^2}{r_2r_3}+\frac{1}{r_1}\right)+\frac{Z_r\,(1-Ka)}{r_1}\right\} \quad (10)$$

The value of Z' is thus composed of 2 parts, a constant one,

$$Z_c'=-\frac{r_cr_c'}{a^2}\left\{Z\left(\frac{a^2}{r_2r_3}+\frac{1}{r_1}\right)+\frac{Z_r}{r_1}\right\} \quad (11)$$

and a second part varying with the position of the regulators,

$$\boldsymbol{Z}_v' = \frac{r_c r_c' \boldsymbol{Z}_r K}{r_1 a} \qquad (12)$$

Automatic regulation is possible only if $\boldsymbol{Z}_v'$ is negligible with respect to $\boldsymbol{Z}_c'$.

In the case of one of the feeders between Hell Gate and Sherman Creek;

$$\begin{aligned}
\boldsymbol{Z} &= 1.044 + j\,1.833 \\
\boldsymbol{Z}_r &= j.33 \\
\boldsymbol{Z} + Z_r &= 1.044 + j\,2.163 = 2.4\, e^{j64^\circ\ 15'} \\
r_1 &= 120 \\
r_2 &= 120 \\
r_3 &= 5.5 \\
r_2 r_3 &= 660 \\
r_c r_c' &= 60\sqrt{3} = 104
\end{aligned}$$

The maximum value of K is 0.08. Thus, $\boldsymbol{Z}_c' = 1.90 - j\,.162 = 1.905 e^{-j4^\circ\ 55'}$ $\boldsymbol{Z}_v'$ can at the most be equal to

$$\boldsymbol{Z}_v' = 0.0229\, e^{-j30^\circ}$$

and is, therefore, negligible. In this particular case, automatic operation is thus possible if the line drop compensator is set at approximately 1.90 ohms resistance. The regulators once started will stop only when the angle between the 2 stations becomes zero with an approximation as determined by the sensitiveness of the primary relay. Once the latter is known, the angle at which equilibrium can be reached can be calculated with the aid of eq 8.

By equating the difference between eq 8 and

$$\frac{\sqrt{3}\,\boldsymbol{E}_{H1}\, e^{-j30^\circ}}{r_2 r_3} \text{ to } \frac{\sqrt{3}\,\boldsymbol{E}_{H1}\, e^{-j30^\circ}\, e^{\pm j120^\circ}}{r_2 r_3},$$

it is obtained that

$$\left(\frac{1 - Ka^2}{r_2 r_3} - \frac{K}{r_1}\right) \left\{\frac{\boldsymbol{Z} + \boldsymbol{Z}_r (1 - Ka)(1 - j\,2 \sin \frac{\theta}{2} e^{-j\frac{\theta}{2}})}{\boldsymbol{Z} + \boldsymbol{Z}_r (1 + K + K^2)}\right\} - \frac{1}{r_2 r_3} + \boldsymbol{Z}' \frac{(j\,2 \sin\frac{\theta}{2} e^{-j\frac{\theta}{2}} - KA^2)}{r_c r_c' \{\boldsymbol{Z} + \boldsymbol{Z}_r (1 + K + K^2)\}} = \frac{e^{\pm j120^\circ}}{r_2 r_3}$$

From which

$$\boldsymbol{Z}' = \frac{r_c r_c'}{j\,2 \sin\frac{\theta}{2} e^{-j\frac{\theta}{2}} - Ka^2} \left\{ \boldsymbol{Z}_r (1 - Ka)\, 2 \sin\frac{\theta}{2} e^{-j\frac{\theta}{2}} \left(\frac{1 - Ka^2}{r_2 r_3} - \frac{K}{r_1}\right) + \boldsymbol{Z}K\left(\frac{a^2}{r_2 r_3} + \frac{1}{r_1}\right) + \frac{\boldsymbol{Z}_r (1 - Ka)K}{r_1} + \frac{[\boldsymbol{Z} + \boldsymbol{Z}_r(1 + K + K^2)]a^{\pm 1}}{r_2 r_3} \right\} \qquad (13)$$

For $\theta = 0$ this gives 2 values, $\boldsymbol{Z}'_1$, $\boldsymbol{Z}'_2$, for $\boldsymbol{Z}'$:

$$\boldsymbol{Z}_1' = \boldsymbol{Z}_c' + \boldsymbol{Z}_v' - \frac{r_c r_c' a^2}{r_2 r_3} \left\{\frac{\boldsymbol{Z} + \boldsymbol{Z}_r}{K} + \boldsymbol{Z}_r (1 + K)\right\}$$

$$\boldsymbol{Z}_2' = \boldsymbol{Z}_c' + \boldsymbol{Z}_v' - \frac{r_c r_c'}{r_2 r_3} \left\{\frac{\boldsymbol{Z} + \boldsymbol{Z}_r}{K} + \boldsymbol{Z}_r (1 + K)\right\}$$

where $\boldsymbol{Z}_c'$ and $\boldsymbol{Z}_v'$ are given by eqs 11 and 12. It is seen that both values vary widely with the factor K, that is, with the position of the regulators, and therefore no equilibrium is possible under the assumed conditions that the difference between eq 8 and $\frac{\sqrt{3}\,\boldsymbol{E}_{H1}\, e^{-j30^\circ}}{r_2 r_3}$ be equal to $\frac{\sqrt{3}\,\boldsymbol{E}_{H1}\, e^{-j30^\circ} e^{\pm j120^\circ}}{r_2 r_3}$.

In concluding, from eqs 9 and 13 it is deduced that, in general, no position of equilibrium can be reached with the 2 stations at angles other than zero. With the 2 station voltages equal in phase and magnitude, equilibrium, and thus automatic operation, is possible if $\boldsymbol{Z}'$ is set at the value as dictated by eq 11, provided that eq 12 is negligible.

H. C. Forbes and H. R. Searing: The discussion presented by Mr. Calabrese answers Mr. Starr's request for details as to the functioning of the regulators and compensator.

The authors agree with Mr. Sweetnam that individual regulation at the network transformer is technically a desirable solution to the problem of network voltage control. A rather complete study of regulation by this method, however, determined that for the conditions in New York City individual low tension regulators or tap changing equipment could not be justified from the economic standpoint. Development of a cheap and rugged tap changer for distribution transformers may alter this picture. Mr. Sweetnam's suggestion that the complications of network operation from numerous sources could be overcome by segregation of network supply so that a given district is served from only one source has some merit, and it is possible that generating stations built in the future will provide the necessary sectionalization so that reliable supply can be obtained from one station. It is expensive and difficult, however, to revamp an existing station to provide such segregation, and in new stations of large capacity complete isolation of bus sections may be required in order to hold the interrupting duty of the circuit breakers to reasonable values. Moreover, the cost of feeder rearrangements so that each district has a supply from only one station may be excessive.

In the authors' opinion, the decision must be made on the facts surrounding a given situation. A district located midway between 2 generating stations can probably best be served by feeders from both stations. A district immediately adjacent to a station will probably receive all of its supply from that station. Furthermore, a new station usually starts up with one or 2 units and during the transition period it is necessary to augment the supply by ties from other sources. Even with these supplementary ties the reliability of such a station in the initial stages of development may not be adequate to serve as the only source of supply to a network district and a feed to the network from adjacent stations may be considered desirable

In view of these considerations the authors think it probable that the future trend of engineering development will be such that applications will be found of the devices and methods of operation described in the paper.

A Compensated Automatic Synchronizer

Author's closure of oral discussion of a paper published in the June 1934 issue, p. 960–8, and presented for oral discussion at the automatic station session of the summer convention, Hot Springs, Va., June 28, 1934.

H. T. Seeley: Mr. Gulliksen questions whether 2 tubes are really necessary for the purpose of compensating for changes in control voltage. There seem to be 2 possibilities in the amplifier design. One is to use d-c for the plate and a-c for the filaments, and the other is to use only d-c for both plate and filament supply. Previous designs have used a-c filament supply and, with this arrangement, it is possible to get 2 point compensation with a reasonable value of plate current by proper choice of bias voltage from a potentiometer across the plate voltage source, as Mr. Gulliksen suggests. However, it appears that if the filament and plate voltages are both low at the same time, the operating point of the plate current relay will be considerably affected. Since there is no relation between low continuous voltage and low alternating voltage, the changes in operating point due to accidental, simultaneous changes in these 2 voltages probably cannot be compensated for by any method simpler than the use of a second tube.

If d-c is used for both the plate and filaments, the operating point must be lowered still further to obtain even 2 point compensation, and the plate current is so small that a sensitive relay is necessary for fast operation. The choice between this and a balanced relay with the extra tube to obtain larger operating forces is a matter of judgment.

Mr. George has pointed out the desirability of 2 settings for a synchronizing relay; a normal setting that will synchronize only under favorable conditions, and an emergency setting, selected by the mere operation of a control switch, that will increase the synchronizing angle to a much larger value than the normal. This is fairly simple with the constant angle type of relay, but the situation with respect to the proportional angle relay is not quite the same. Here the relay operating angle is determined automatically by the frequency difference, and it would be disadvantageous to change this relation. The setting that would have to be changed to give quicker synchronizing under unfavorable conditions is the frequency difference setting. As far as the proportional angle feature of the present relay is concerned, this setting can be increased to 0.375 cycle per second (as has already been done in one special case) if the breaker time does not require more than 45 deg advance at this frequency difference. Even these 2 limits can be exceeded somewhat by a sacrifice of accuracy at the smaller frequency differences, if necessary.

The means necessary for providing the 2 frequency difference settings are not yet worked out, although I am sure they can be if the demand warrants it. However, it should be pointed out that the proportional angle synchronizer can be given a high initial frequency difference setting (com-

pared with the constant angle type) without increasing the synchronizing error introduced by the relay characteristics, and, therefore, the added usefulness of the dual setting is somewhat less than in the case of the constant angle types.

Load Totalizing in the New York Area

Discussion and author's closure of a paper by F. Zogbaum published in the June 1934 issue, p. 886–9, and presented for oral discussion at the automatic station session of the summer convention, Hot Springs, Va., June 28, 1934.

R. C. Buell: Mr. Zogbaum has described a very interesting and excellent installation of telemetering equipment. I have always thought that a system operator should have available before him instantly as much information as possible in order to function properly and speedily. The thermal converter inherently has some time delay in giving its load indication; it therefore can give the operator no clear indication of swinging loads, instability, or sudden changes in load.

This paper indicates a very high degree of accuracy for this equipment. Our experience indicates that there is a departure from such accuracy with time and this, together with the effect of ambient temperature, power factor, voltage variation and the like, tends to produce a result to give an accuracy more nearly in the order of 1 per cent for a simple combination of transmitter, channel, and receiver.

In any device that depends on heating for its results, one is always interested in precautions necessary to prevent burnout. I would like to ask if protective relays to short out the thermal converters were considered, and if any experience has been obtained which indicates that such relays are not necessary.

L. O. Heath: Another item of particular interest in connection with the thermal converters used in this installation is the fact that their accuracy is not seriously impaired even at power factors as low as 50 per cent. The very low burden involved on the instrument transformers, namely, approximately 3 volt-amperes on both current and potential transformers, is another factor which generally tends toward accuracy in such metering.

M. E. Reagan: Mr. Zogbaum's paper tells of the simplification and economics that are possible with modern telemetering equipment. It shows clearly the present trend toward the centralizing of dispatching control.

Such systems are successful only because the equipment used is extremely reliable. The manufacturers have done their part in producing satisfactory apparatus. However, the system of instruments and meters must be operated over an equally reliable line. The importance of the cable requirements or specifications cannot be overemphasized. They must be maintained in a high order of electrical quality to make such a system feasible.

The next step in utilizing the possibilities of economy is to add remote control of the load to the dispatcher's board. Then he would have better service at his fingertips. He would obtain faster response to his orders especially during emergencies when delays are costly. It is also probable that he would obtain even better load equalization or distribution, which reflects directly in the economy.

E. J. Rutan: It may be of interest to present some data in connection with the initial investigations of the performance of the telemetering and totalizing system which Mr. Zogbaum describes in his paper. This system was selected as a result of comparative tests made in the test bureau laboratory. At the time, the test bureau had installed in its laboratory the 2 terminals of a 5-mile telephone cable circuit. This installation had been made in order to conduct development work on telemetering systems and on methods of transmitting phase-angle measurements, which were described in a paper by Messrs. Forbes and Searing. (Electrical Engineering, June 1934, p. 903–9.)

Several telemetering systems were tried out in the laboratory and were subjected to various tests, using as a guide the proposed A.I.E.E. standards for electrical recording instruments. It was thought that telemetering systems should perform about the same as recording systems and, therefore, the test bureau has used these standards in determining performance characteristics. The tests using the telephone cable circuit also permitted obtaining data approaching operation under normal and faulty telephone circuit conditions.

After the Leeds and Northrup equipment had been decided upon, arrangements were made with the manufacturer so that one of our engineers visited their factory at the time they had assembled the equipment for trial operation. At that time we made our acceptance tests because it would not be convenient to perform these tests after the instruments had been installed in widely separated stations. The tests on the individual parts were deferred until the equipment was received but over-all tests, particularly with reference to what is known in recording instruments as friction influence, were performed at the plant. This test, which we consider a most important one, determines the amount of change in the electrical quantity at the transmitting element which is necessary before an observed change takes place in the receiving element. This might be called the sensitivity of the system. Our tests disclosed that on thermal converters developing 60 millivolts for full range indication a change of 0.2 millivolt caused the receiving device to function. This change corresponds to approximately 0.3 of 1 per cent of full scale indication and shows that the instrument is ready to follow extremely small changes. The other important characteristics have been discussed in the paper.

Since the installation of the device, the maintenance has been carried on by the test bureau. A regular program was set up based on suggestions from the manufacturer, which it was hoped could be lengthened in order to save money. Our experience with other telemetering systems has shown that it is desirable to have the maintenance period very short during initial operation. This practice permits clearing up minor defects and maintains the confidence of the operating personnel in the new device. Such a practice was justified in this case. Operation discloses that galvanometers require periodic mechanical balance on about a weekly basis. On some of the recorders in which a horizontal type of drive is used, trouble developed due to wear in the bearings and gears. These recorders are to be changed so that they will have the vertical type of drive similar to most of the others in this installation. Other troubles which resulted in failure during operation disclosed 1 defective resistance coil, 1 loose connection on the d-c side of the thermal converter, 2 loose wiring connections on the measuring side of the thermal converters and, in addition, on 5 occasions faulty indications were caused by workmen vibrating the panels while working nearby. This caused the galvanometers to get out of balance. On the telephone circuits on 3 occasions fuses blew disconnecting the lines.

From the nature of these troubles it is quite obvious that they were or can be readily cleared up and it is expected that the system will operate with little future trouble. The program of maintenance initially involved a weekly inspection which includes cleaning, oiling, and balancing. This continued for 3 months, after which the inspection was put on a 2 weeks' basis. Beginning July 1, 1934, we expected to place the maintenance on a 3 weeks' basis, finally working up to a monthly inspection. It should also be noted that these recorders are cared for daily as far as ink and chart maintenance is concerned.

F. Zogbaum: In preparing this paper the author had in mind a brief description of the system involved so that those interested could get a general picture of one of the most modern load totalizing systems. However, it seems desirable to amplify the paper as follows.

The slight time delay inherent in the thermal converter is not considered to have any serious effect upon load dispatching where the load is large and concentrated and where load swings are of a somewhat milder nature than would be experienced on some high tension interconnected transmission lines. The thermal converters and their associated receivers will indicate 90 per cent of a full scale change in the metered power in 12 seconds and 100 per cent well within 1 minute.

As far as departure from original accuracy is concerned it is pointed out that both the transmitter and receiver are provided with wide range adjustments by which a high degree of accuracy may be maintained; also, the lack of moving parts in the thermal converter transmitter further minimizes the possibility of error. Normal fluctuations in ambient temperature have no appreciable effect upon the thermal converter or the potentiometer type receivers and any change in telephone channel resistence due to temperature will have no effect on the accuracy due to the null method used.

Power factors as low as 50 per cent and voltage variation do not seriously impair thermal converter accuracy under ordinary operating conditions.

In regard to the performance of the thermal converters under short circuit conditions, no special precautions, such as lock out relays, are used for protection. Laboratory tests have shown that the thermal converter will withstand 20 times normal current for 2 seconds, thereby providing a safe margin for most faults encountered.

Electronic Regulator for A-C Generators

Discussion and author's closure of a paper by F. H. Gulliksen published in the June 1934 issue, p. 877–81, and presented for oral discussion at the automatic station session of the summer convention, Hot Springs, Va., June 28, 1934.

G. W. Garman: This paper describes a very interesting application of electron tubes. The data given shows that excellent results have been obtained.

Electron tube devices are relatively new and require a certain amount of knowledge and experience before confidence can be instilled into those who are to use them. Furthermore, the present cost of electronic tube devices has limited their application where they are competitive with the equipments generally in use at the present time.

We have been actively engaged in the development of electron tube regulators for more than 8 years. During this period particular emphasis has been placed on the needs of a central station type regulator. While the general form of attack has been remarkably similar to the regulator described by Mr. Gulliksen, the design of the particular elements is very different.

As may be noted in Fig. 1 of this discussion, the voltage determining means is composed of 3 copper oxide rectifiers and a thyrite bridge. To eliminate the disadvantage of single-phase regulation, the voltages of all 3 phases are rectified and then added together to obtain a single continuous voltage that is a function of all 3 alternating voltages. This continuous voltage is then impressed on the thyrite bridge.

The excitation circuit consists of a 3-phase grid-controlled thyratron type rectifier. Usually the only reliable power source is either that of the generator being regulated or that of the bus supplying power to the synchronous condenser. With a single-phase short circuit, the single-phase rectifier would be inadequate.

Control of the thyratron output or field excitation is obtained by superimposing a controlled continuous voltage upon a fixed alternating voltage. The fixed alternating voltage lags the anode voltage by 90 or 120 deg depending upon the type of rectifier system used. By varying the superimposed continuous voltage the field excitation can be smoothly varied from zero to the maximum value. This superimposed voltage is obtained from the thyrite difference voltage after it has been amplified by means of the 2 pliotrons operating in parallel.

It has been found and can be proved mathematically that with no inherent inertia in the voltage regulator hunting will occur due to the inertia in the field circuit of the exciter. It can be shown that to prevent this hunting it is necessary to introduce into the circuit a voltage that is proportional to the rate of change of the synchronous machine field or exciter armature voltage. The voltage drop across the resistor in a series resistor and capacitor circuit when connected across the exciter armature furnishes the required voltage. The other resistors and capacitors in the grid circuit of the pliotrons form a damping and quick response circuit that has been found necessary under certain conditions.

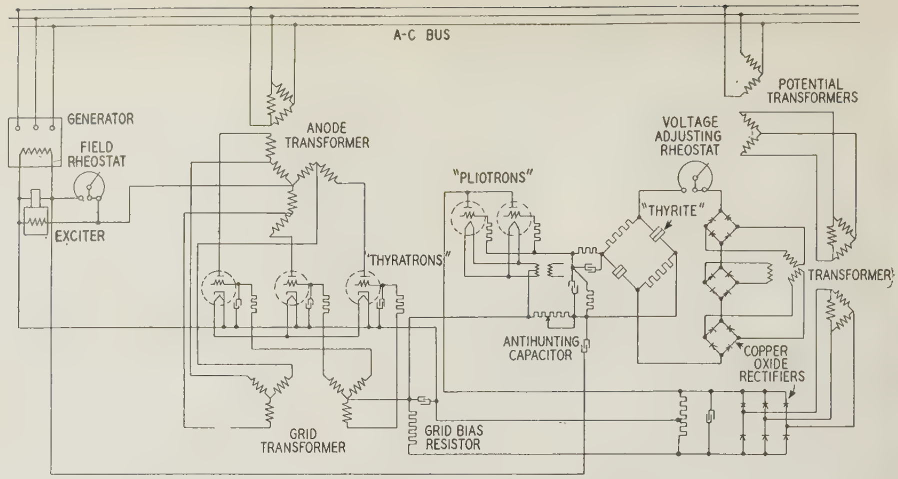


Fig. 1. Circuit of electronic tube regulator

To avoid using exciters with special field windings, it is only necessary to add an additional capacitor in the antihunting circuit. The exciter can then be self-excited in the normal manner with the advantage that the regulator can be placed into or taken out of service with the same ease as the mechanical type of voltage regulator.

In reviewing those factors which add to the reliability of the regulator, copper oxide rectifiers are used with a conservative rating to convert the alternating voltage into a continuous voltage. The 2 pliotrons in the regulator are operated in parallel and lightly loaded to give long life. A failure of one of these tubes will cause only a fraction of a per cent change in the regulated voltage. Because a 3-phase type of rectifier is used, a failure of one of the thyratrons will cause only a fraction of a per cent change in the regulated voltage. Furthermore, the voltage rating of the anode transformer is such that normal excitation can still be obtained even though the primary supply voltage is reduced to half, or less, of normal.

The variation in the regulated voltage of the synchronous machine, from no load to full load, is the same as for the mechanical type voltage regulators; namely, less than ± 1 per cent. This voltage variation can of course, be reduced by the use of tubes with a higher amplification factor or by means of another pair of amplifier tubes. It is thought that this additional refinement is not required in the majority of cases.

Regulators of this type have been in practically continuous operation for over 3 years. Operation has been satisfactory and tube replacements have been a minimum.

With this service record on a developed and successful device, the question arises: why has this type not been commercially exploited to a greater degree? The answer lies in the high degree of accuracy and perfection in the mechanical types of regulators and their relatively lower costs at the present time.

The electronic tube type regulator goes further than mere voltage regulation. It furnishes and controls the exciter field current. There is no reason why synchronous machine field current cannot be supplied directly provided the requirements do not exceed the tube capacity. The future of this type of control will, therefore, depend upon obtaining large sized tubes at a cost competitive with existing methods of excitation.

A limited number of direct excitation type electronic voltage regulators have been made. The largest installed regulator supplies and controls the excitation of a 15,000-kva synchronous condenser. The full load excitation is 560 amp at 135 volts. This regulator exciter has been in service for approximately 8 months.

H. T. Seeley: I think Mr. Gulliksen is to be complimented on obtaining fast and accurate regulation of circuit voltage by a booster, because the regulation of a booster is inherently more difficult than that of a generator of equal rating. For example, a sudden change of 5 per cent in source voltage would require an immediate change of about 50 per cent of full excitation on a booster with a rating of plus or minus 10 per cent of circuit voltage.

In reading Mr. Gulliksen's paper, I was unable to reconcile the mention on p. 877 of a regulator which "does not need any dry cell battery" with the description which followed this statement, and possibly others were similarly confused. I now understand, from the presentation, that the regulator without dry cell battery uses a glow tube as a voltage standard and is not the same regulator described in detail in the paper.

We have made factory installations of regulators using glow tubes as voltage standards and have found them quite satisfactory where ordinary accuracy is required. One of these is described in the paper by C. B. Foos, "A Vacuum Tube Controlled Rectifier," published in the April 1934 issue of Electrical Engineering.

Our experience with the relative speeds of response of a tube regulator on pick-up and dropping load is the same as that mentioned by Mr. Gulliksen in his reference to Figs. 3 and 4. The reason for the difference in response may be made clear by the following considerations. The speed of build-up may be increased to any reasonable value required merely by increasing the source voltage available for the tubes, but when a large sudden decrease in excitation is required, we can only put a negative charge on the grids of both thyratrons, and this cannot stop their conduction, so the rate of build-down is determined entirely by the time constant of the field circuit. These conditions may be improved only by adding series resistance on the field circuit to reduce its time constant and a compromise is necessary in this regard because excessive losses in this circuit may be objectionable.

C. W. LaPierre: In the author's Fig. 7 covering the lamp bridge detector no special provision is made to take care of the second harmonic output of the bridge. This second harmonic arises from the 120-cycle pulsation in filament resistance corresponding to each half wave of 60-cycle current. It is always present whether the bridge is in balance or not and its magnitude is a function of the thermal time constant of the lamp filament. For some types of filament construction the second harmonic is so large that it tends to obscure the small fundamental frequency voltages which indicate unbalance in the bridge.

For some time we have been experimenting with a lamp bridge designed to give a result several times as precise as that covered in the present paper. We have found that a precision of better than a few tenths of one per cent could not be consistently obtained over a long period with ordinary commercial lamps. With special care in the lamp construction, a precision of a few hundredths of a per cent is feasible. It would be of interest to have data on the actual balance voltage over a period of time of the bridge in the present paper.

As to the lamps, I would like to know whether ordinary commercial lamps are used and also their rating.

Philip Sporn: Electronic voltage regulators have been in service on the American Gas and Electric Company's system for a little more than 4 years, and considerable valuable operating experience has been gained during this time.

The first of these regulators was installed in March 1930, controlling a 15,000-kva synchronous condenser at our Howard substation near Mt. Vernon, Ohio. It consisted of a 3-phase thyratron rectifier supplying excitation to the field of the condenser exciter. At the time of installation this equipment was frankly termed experimental, and 2 different schemes of controlling the thyratron output, one entirely by vacuum tubes and one partly mechanical, were provided. This regulator has now had approximately 35,000 hours of actual service and has proved to be as reliable as the mechanical types of regulators. Because of the type of circuit employed in the vacuum tube scheme of control, it was found to be less satisfactory than the mechanical scheme, and as a result it is planned in the near future to replace both types of control with a newer type entirely electrical which has proved its worth in actual operation. Practically the only point of wear experienced has been at the thyratron tubes. These have given an average life of approximately 15,000 hours, and one tube functioned 17,800 hours before failure.

Two regulators using the newer type of vacuum tube control mentioned above for the thyratron output were installed in April 1931. One of these was used with a 25,000-kw and the other with a 20,000-kw generator, both at our Glenlyn, Virginia, plant. Like the earlier regulator, these supply excitation for the fields of the main exciters. These regulators have not been in service as continuously as the earlier one, having been used only approximately 18,000 hours each. The control scheme appears to be entirely satisfactory, and the only source of trouble has been failure of thyratron tubes, the average life of a tube being approximately 13,000 hours.

As a step further in advance, a fourth electronic regulator was installed in September 1933, on a 15,000-kva condenser at Scranton, Pa., this time supplying the excitation for the condenser field itself directly from the thyratron tubes. Since placing in service, this regulator has been in use almost continuously. A few troubles have developed, none of which appear to be fundamental; we are coöperating closely with the manufacturer in this and we believe they will be successfully eliminated. However, it is still too early to say definitely that all troubles have been overcome, and the service hours have been insufficient to furnish data on tube life. We are hoping to be able to present before the Institute in the not too distant future further and more technical details on all these tube applications.

F. H. Gulliksen: With reference to Mr. Seeley's discussion, I wish to mention that the new type of voltage regulator which does not need a dry cell battery uses a diode as the voltage indicating element. The principle of operation of this new regulator is somewhat similar to the type *AT-1* regulator described in the present paper.

Mr. LaPierre asks about the characteristic of the lamps employed in the monitor bridge. These lamps are standard 25-watt 125-volt type *S-11* mazda lamps. Data on the actual balance voltage of the bridge over a period of time are unfortunately not available; but the balance point for the monitor remains with $\pm 1/10$ of one per cent during a period of at least 2 or 3 days.

Flashover Voltages of Insulators and Gaps

An A.I.E.E. committee report, June 1934 issue, p. 882–6.

Selection and Performance of Suspension Insulators

Philip Sporn, E. L. Peterson, and V. A. Mulford, June 1934 issue, p. 936–42.

High Voltage Insulators

W. A. Smith and J. T. Lusignan, Jr., June 1934 issue, p. 969–73.

The Suspension Insulator

K. A. Hawley, June 1934 issue, p. 895–8.

Radio Influence Insulator Characteristics

G. I. Gilchrest, June 1934 issue, p. 899–902.

Recent Developments in Suspension Insulators

G. M. Barrow, June 1934 issue, p. 867–70.

A New Porcelain Post Insulator

G. W. Lapp, June 1934 issue, p. 922–5.

Discussions of a group of papers presented for oral discussion at the session on insulators of the summer convention, Hot Springs, Va., June 28, 1934.

Sidney Withington: Emphasis may appropriately be given to a number of points mentioned in the various interesting and timely papers presented on the subject of porcelain suspension insulator design and operation.

There has been a tendency to differentiate somewhat sharply between "mechanical and electrical strength" and "ultimate mechanical strength" in discussing suspension insulator characteristics. It should be borne in mind that the so-called "electrical" failure of an insulator under stress is very likely to result in rupturing the insulator under service conditions because of the power arc which follows the failure, especially in railway distribution circuits which are rigidly grounded and involve considerable power capacity. It seems logical, therefore, to consider that the ultimate mechanical stress of an insulator is not of vital importance, but that the mechanical and electrical

strength is the principal criterion. It is, of course, of vital importance to avoid dropping the conductors in the event of an insulator failure, and this can best be accomplished by emphasizing a high mechanical and electrical strength rather than a high ultimate mechanical strength.

For a number of years some importance has been attached to the requirement that insulators contemplated for a given service be subjected to the standard temperature cycle test under mechanical stress, in order to insure that the wedging action of the pin will not be a factor in the ultimate failure of the insulators in service. This was proposed in the report of the electrical section of the American Railway Association, Sept. 26, 1932, p. 40, and some railroads have adopted this as a requirement.

The time factor for insulators under stress is of primary importance. It is apparent that the long-time tensile strength is definitely less than that which would be recorded by the test stipulated in the A.I.E.E. standard test specification. A factor recognizing this reduced value should be applied in designating the rating of the insulator. This was suggested in the report mentioned in the previous paragraph.

It is desirable that the time-stress tests be carried on outdoors or with other means for varying the temperature over a reasonably wide range if full value of this form of test is to be obtained. The mere "alternate freezings and thawings each year" mentioned by Mr. Hawley, such as occur frequently during the winter season, cannot be said to constitute a temperature cycle. For this reason 2 years of such test cannot be said, without qualification, to be sufficient to demonstrate the ultimate life of the insulator. It has been the experience of a number of insulator users that insulators of a given design have performed satisfactorily for 4 or 5 years and have subsequently shown definite signs of distress.

In the assembling of suspension insulators with a resilient compound, such as hot asphalt, it is necessary to take care that the composition or quantity of the compound used is not such as to cause an explosion within the cap in the event of puncture of the insulator. Certain types of insulators have shown a tendency toward troubles of this kind, which on occasions have caused a complete rupture of the cap under obviously high mechanical pressure, which of course has resulted in the parting of the insulator and dropping the line conductor.

The vulnerability of insulators to damage by stones and other materials may be of particular importance in selecting the insulator design for a given service, especially along railroad right of ways where the stone ballast provides effective ammunition for use by mischievous trespassers in some localities. In such cases, it may be found desirable to adopt a rugged mechanical design, even at some sacrifice of electrical refinements.

The continual change in insulator design details by manufacturers may be embarrassing to the users of insulators. Rather important details have been modified without advice to the purchaser or any change of designation. Some of these changes, as has been pointed out in one of the papers under discussion, have more or less seriously affected the reliability of the design for specific service. In spite of the apparent confusion which frequent changes in detail may involve in catalogue data, etc., modification of even relatively small details should be frankly noted by the supply company for the advice and guidance of the consumers.

The statement that porcelain is less susceptible to vibration than hardware is especially interesting. On the New Haven Railroad electrification a number of instances have been experienced from time to time which have seemed to indicate that vibration has caused insulator porcelain failures. Measures adopted for reducing the vibration of the insulators in such locations have produced valuable results at these locations. Possibly the type or kind of vibration may be an important factor.

It is of importance, as has been mentioned, that each individual insulator assembly be subjected before shipment to a routine tensile strength test, as required in the A.I.E.E. test specification. Instances have occurred where a failure due to an undetected flaw in the hardware has dropped a conductor as soon as stress has been applied in the field. This type of failure is very serious, as it is likely to cause personal injury to members of the construction force engaged in the installation.

In connection with developing data on the application of suspension insulators to individual service, the compilation of standard recommended practice under varying conditions of circuit characteristics, temperature variation, moisture, salt, air pollution, etc., should be of value as a guide to the designers of transmission lines. Some data of this nature, especially in connection with railway problems, were proposed in the American Railway Engineering Association proceedings for 1926, p. 147.

It is suggested that when the A.I.E.E. standard insulator specifications are next revised they be modified to include thermal tests under mechanical stress, as indicated above, and also include a recognition of the ratio between the mechanical and electrical strength as applied on a short-time basis in a testing machine, and that over a relatively long period of time; the long-time values would more nearly approach conditions actually experienced in service, and upon these ultimate strength designations and factors of safety should logically be based.

R. W. Sorensen: The insulators and the service rendered by them, described in the papers by Messrs. Hawley, Smith, and Lusignan, and Sporn, Peterson, and Mulford, show a remarkable insulator evolution since the time of the contemporary discovery in 1917 by the late Prof. Harris J. Ryan and myself, when on 2 separate and distinct testing programs we found that certain insulators not in use on transmission circuits had a failure rate equal to others of the same vintage and manufacture which were in use on power lines and were thus subject to voltage stresses. All developments from the time of this turning point in the explanation of the cause of insulator failures have shown that the mechanical, rather than the electrical, problems predominate and are the problems which, as yet, remain to a large extent unsolved in the great program of obtaining insulators uniform as to performance, and having a life equal to or greater than the life of other apparatus materials and devices used in power transmission.

The papers under discussion show the ability and ingenuity of engineers in overcoming the difficulties involved in the production of high grade insulators and in devising methods of testing and inspection of insulators which insure, for the most part, the meeting of prescribed standards. Nevertheless, our present standards rules, governing the grading of insulators, seem somewhat deficient in providing a way to determine the life of insulators under long-time mechanical and electrical loads. For this reason, it appears to me desirable and, in fact, almost absolutely necessary that more data from long-time mechanical loading tests, similar to the data presented by Messrs. Sporn, Peterson, and Mulford, be made available. As a contribution toward this goal, I am planning to present at the Pacific Coast convention results of some insulator studies which include long-time loading tests.

Briefly, as an indication of what these tests show with respect to this problem, I would like to call your attention to the relative ability to stand long-time load tests of 8 of the several lots of insulators which I have tested. On the basis of a life expressed in terms of pound-day-load to cause failure, the relative values shown by these 8 groups are as follows:

5.0...6.0...8.8..12.7..13.3..13.4..14.0..17.1

With the best lot showing a value more than 3 times that of the poorest lot, it is quite obvious that much can be learned regarding insulator selection from long-time tests, and that much aid can be given in making a proper selection when we have learned enough about such tests to include them in our insulator specifications.

H. F. Brown: The symposium on insulators presented at the summer convention is of particular interest, including as it does 5 papers from 4 of the leading manufacturers' representatives, one from well-known "consumer" representatives, and a paper from the power and transmission committee relative to the standardization of flashover data for insulators.

The paper by Messrs. Sporn, Peterson, and Mulford is of particular interest to other consumers in that it presents a critical analysis of the performance of insulators of various manufacture over many years. It is apparent to nearly all insulator consumers that while most manufacturers have "standardized" on the outward appearance and dimensions of both suspension and pin insulators, the internal construction still varies greatly among the various leading manufacturers; and often, as Mr. Sporn points out in this paper, the internal construction varies from time to time in the same type of insulator by the same manufacturer, thus rendering long-time tests more or less meaningless as to performance of present day designs.

I believe with the authors of this paper "that the present A.I.E.E. standard tests for suspension insulators are not in themselves sufficient to furnish a basis for detecting all insulators of inferior design and manufacture, or for comparing competitive makes of insulators." Although it is probably true that "modern suspension insu-

lators of proper design and manufacture, properly selected and correctly applied, can be expected to give satisfactory performance over a long period of time. . . . ." it is, nevertheless, a difficult problem for the consumer to determine just what the "proper design and manufacture" is, when the manufacturers themselves are apparently not in agreement on many of the important details covering these points. For example, Mr. Hawley in his paper covering the improvements made in suspension insulator design during the past few years, gives comparative data on pin or bolt design, with 1, 2, and 3 steps, arriving at the conclusion that the 1-stepped bolt, especially the single-stepped bolt with curved shape, is not as efficacious as the 2-stepped bolt. Mr. Barrow in his paper demonstrates just as conclusively that the single-stepped bolt, with curved shape, behaves much better than the multi-stepped pin on repeated changes in temperature and load. Mr. Gilchrest points out the efficiency of metallic coatings applied to the glaze for improving the "radio influence" characteristics of insulators, while Mr. Lapp in turn shows how these effects may be reduced by changes in the shape of the top of the insulator, without resorting to special coatings applied to the glaze. In each of these details the manufacturer no doubt has a sales argument, which is left to the consumer to evaluate, if he can.

Not all of the large consumers of insulators have on their staff engineers who are specialists on insulator design, and they in turn must lean heavily on the engineering staff of the various insulator manufacturers for the salient features of design, and on some standard specifications such as those of the A.I.E.E. for guidance in determining their selection of proper design for a particular installation or application. There may be a few isolated instances where insulators already installed may be expected to perform, as Mr. Sporn indicates, "satisfactorily for 50 years"; but experience has proved that there are more instances where both pin and suspension designs which have satisfactorily passed all A.I.E.E. tests, including thermal cycle tests and long (2 year)-time load tests, have so failed in service, and with an increasing percentage of failures each year, so that they have had to be replaced completely within 5 or 6 years of their installation. Very possibly some of these insulators were overrated, but the tests applied were not able to demonstrate that fact.

In connection with thermal tests of suspension insulators, these are now specified to be made between the limits (approximately) of freezing and boiling water. Since the cement in most suspension insulators is set under steam, at high temperatures which are probably never again experienced in service, it would seem that there is something to be said in favor of changing the temperature limits of the A.I.E.E. thermal cycle tests to, say, minus 20 deg F and plus 150 deg F, as more nearly representing actual service conditions.

It is well known that the leading insulator manufacturers have not only pooled their important patents covering details of the so-called "standard" designs, but have as a natural result entered into price agreements as well, so that the purchaser has little to guide him in his choice other than "reciprocity buying," unless there are definite data as to a better product which can be demonstrated by tests other than long time performance. It would seem that the manufacturers should not only be in agreement upon the essentials of internal as well as external design, but there should also be some agreement among them as to manufacturing and assembling methods. For example, in his paper detailing the manufacturing methods of suspension insulators, Mr. Smith specifically mentions a time interval between cementing on the cap and the cementing in of the pin. Some manufacturers perform both of these cementing operations at the same time. If there is any more merit in one method than the other, it would seem desirable to standardize on that method, rather than leave it to the consumer to determine which method may give a better performance of the product. Numerous other differences in manufacturing will occur to those familiar with insulator manufacturing and assembling. While many of these details might be considered "trade secrets," it would doubtless advance the art materially if some of these differences could be eliminated by agreement among the manufacturing engineers.

Most of the so-called "standard" insulator designs, particularly of suspension insulators, have been developed specifically for the great network of cross-country transmission lines which have grown so rapidly within the past 2 decades. Their successful performance in such service is not necessarily an indication of equal economic performance on the catenary and distribution systems of electrified steam railroads, although they have, of necessity, been so applied. It is my opinion that there is a large field for improvement in design of both suspension and pin insulators for this service. Less fragile porcelain shapes, the grading of units in strings, having in mind the steeper potential gradients resulting from grounded circuits, and greater mechanical strengths have economic possibilities if they can be successfully combined.

Theoretically, there should be no reasons why the insulator should not last for as long a time as any other part of the transmission line, because, with the exception of the exposed surfaces of the metal cap and pin, it is an assembly of inert materials. The manufacturers have made great strides in the past 20 years, and have contributed much to the success of power transmission at very high voltages. With the extensive laboratories and facilities for research at their disposal today, progress during the next few years should be, and probably will be, just as rapid.

C. Francis Harding: After reading all 7 papers of this symposium it is evident that the recent developments in design, manufacture, and usage of all types of porcelain insulators have been most satisfactorily outlined. It is unfortunate that the corresponding characteristics of glass insulators which have been attracting considerable attention and warranting increasing usage during the last few years, were not represented in a paper in order to complete adequately this symposium.

Another important consideration which might well have been included in this series is a more detailed analysis of the effects of humidity upon flashover of both glass and porcelain insulators, particularly under impulse tests. An early paper by Littleton and Shaver before this Institute indicated the rather surprising effects of humidity upon such flashover values which were obtained in the laboratories of the Corning Glass Company and confirmed in the high voltage laboratory of Purdue University. This paper might have been included in the bibliography to advantage. It is believed that tests under surge conditions of all types of insulators exposed to variable and particularly high humidity or rain should be reported in the near future. Test values so obtained are known to be very different from corresponding 60-cycle values and of course represent the conditions under which failures frequently occur in service.

Another cause of mechanical failure which has been given inadequate attention is the probable lowering of the ultimate strength of insulator materials under repeated vibration, a condition to which the insulators of the larger lines are continuously subjected. As it is well known that some of the materials used in the assembly of insulators, particularly portland cement and possibly the hardware and insulating material itself, are considerably reduced in ultimate strength after subjection to several hundreds of thousands of mechanical vibrations, it is hoped that laboratory tests closely simulating line vibration conditions may be developed to determine the extent of strength reduction caused by such vibrations in service.

W. A. Kates: In the first paragraph of Mr. Barrow's paper, he notes that the details of his unit's cap and pin are so shaped as to resolve mechanical load into compressive stresses in the porcelain, and he contrasts this fact with the tensile and shear stresses in older designs. On p. 869, however, he notes in several instances that the pin pulls down or nests into the cement in adjusting its position under load. Figure 4 illustrates this also. I believe that further discussion of the means of eliminating tensile stress would be in order. The comparison of the insulator with keystone, arch, and buttresses is hardly permissible. Load supported by the keystone of an arch is supported with an accompanying yield of the arch. The arch is not attached to a superimposed structure. Were it so attached, tension would occur at the upper surface of the arch or at the upper ends of the buttresses. In the diagram, Fig. 1*b*, if the load is resolved into forces acting outward toward the cap, a zone of tension will obtain at the upper end of the pin hole. This conclusion is inevitable regardless of whether one considers the force exerted outward in a bursting manner or in axial shear. A corresponding zone of tension obtains at the lower edge of the cap by similar reasoning. The existence of these zones can be demonstrated by photoelastic studies. The design is, therefore, an attempt to minimize the effect of these tensile stresses rather than one which resolves the load entirely into compressive components. Tensile stresses still occur.

A considerable part of the paper is devoted to a discussion of the elimination of wedging. Even after considering this dis-

cussion, I would like to inquire the difference between the phenomena shown by the changing slope of the curves of Fig. 4 and the process of wedging.

In Table I I note that for the compression type insulator the time-load strength for one week is only 11.5 per cent greater than that for 2 years. Does the author believe that one week time-load test can be substituted for a 2-year test if proper allowance is made?

Referring to the same table, do the time load tests all include equal cyclic variations? In the text the author states "time load tests through several seasons of normal weather and temperature changes is an indication of the ability of the compression type to take care of thermal stresses."

In the last paragraph it is stated: "the time-load test is inherently a natural basis for measuring service performance, as the degree to which load and temperature variations could be accelerated without insulator failure constitutes a measure of comparative merit." If this is correct, why was a 48-hour cycle test over a 140 deg temperature range believed to be an indication of design characteristics more satisfactory than the A.I.E.E. immersion test of 20-min cycles over a temperature range of 166 deg F?

In the testing of a large number of glass suspension insulators, we have found that electrical failure is merely an indication of initial mechanical failure. This can be readily determined by visual inspection of the transparent shell. I would like to ask the author if his experience has shown that the same is true of porcelain. Is the electrical failure merely an indication of a mechanical crack? If not, how has this been determined?

The Institute Standards, paragraph 41-301, mentions 3-sec axial pull of 40 per cent of the rated ultimate strength. It has been our experience with glass insulators that this time is entirely too short to indicate a satisfactorily uniform product and we have, therefore, substituted a 5-min test of the same per cent of rating. Would the author suggest the use of a combined mechanical-electrical test as a factory production test, and if so, how long a time of application does he recommend?

Commenting now on Mr. Hawley's paper, on p. 898 is a summary of a number of time-load tests, and these tests are cited as demonstrations of design improvement. In some of these tests the number of units was 3, in others it was 6, in others 12. A consideration of the mathematical theory of uniformity of quality in a manufactured product indicates that these numbers are rather small from which to draw conclusions pertaining to an object which must be manufactured with uniformity and in large quantities. These values may be on the peak of the quality curve, or on one slope, and formation of conclusions from 3 figures is hazardous. It has been the experience of the speaker and his associates that lots of 12 are none too large for obtaining data for generalization, and 20 to 30 are preferable if cost permits.

I would like to ask Mr. Hawley concerning the electrical failure of porcelain. As mentioned in the discussion of Mr. Barrow's paper, we have found that with glass electrical failure is merely an indication of initial mechanical failure. I would like to ask the author if his experience has shown that the same is true of porcelain. Is the electrical failure merely an indication of mechanical crack? Or is it another type of failure and if the latter, how has this been determined?

I would also like to ask Mr. Hawley whether his experience indicates that the combined mechanical-electrical test outlined in the Institute Standards, paragraph 41-301, is indicative, or if longer time of test is preferable.

Commenting on both papers in general, I note that both titles imply broad consideration of the improvement of "the suspension insulator." Perusal of the papers indicates a consideration of only the 10 in. cap and pin design as composed of hardware and a porcelain shell, assembled with portland cement. As this implication is so patent and so broad it seems only fair to note here that a substantial portion of the suspension insulators purchased in 1934 are not of the cemented type. Other types are available, have demonstrated their advantages, and are finding an increasingly broad usage.

Both papers discuss designs which have been subjected to quite extensive tests. Presumably each has been designed for carrying a specified service load over a long period of time. Unit loadings over the cap surfaces are much less than in the pin hole and therefore the pin holes and pin designs have been given largest consideration. Mr. Barrow's design is that including a single load bearing surface on the pin. Mr. Hawley adheres to the multiple stepped construction and notes the inadvisability of large masses of cement in the pin hole. A third one of the larger insulator manufacturers lists in his catalogue 4 different kinds of pins including the multiple stepped, spring supported, and flanged types, and one combination of 2 of these. This variety and the emphasis and mathematical proof supporting each one of the variety excite especially careful consideration of any one type making broad and exclusive claims to correctness while utilizing the same cement, porcelain, and metal. A true test of efficiency of design is not a discussion of the theories but can best be measured by the results. Loads of 25,000 or even 100,000 lb can be supported by single unit composite structures of vitrified shells and metal parts if these are made large enough. I think it would be interesting if, in presenting papers such as these, the results obtained in described tests were not only given in pounds per insulator but in pounds per square inch of load bearing surface, pounds per cubic inch of volume, or some similar figure. Figures such as these would enable those not so intimate with insulator design to form an opinion of the merit of a particular unit in terms calculable for any insulator regardless of size or shape. Thus the engineering design of an insulator having a 4-in. diameter could be compared with that of an insulator having a 6-in. head even though their ultimate strengths differ greatly.

C. L. Dawes and Reuben Reiter: This discussion does not apply to any particular paper but is submitted at the request of the insulator committee. For more than a year research involving power-frequency measurements on suspension insulators has been conducted at the Harvard Engineering School. Practically no investigation of this character has as yet been conducted on power line insulators. By means of our high voltage bridge we are able to measure with some precision the power loss, the power factor, and the capacitance of suspension insulator disks at power frequencies. These quantities are measured as functions of 2 parameters, voltage and mechanical stress. With specially designed mechanical apparatus it is possible to apply tension to over 20,000 lb and yet make electrical measurements. We find, however, that it is not safe to stress standard disks to much over 12,000 lb.

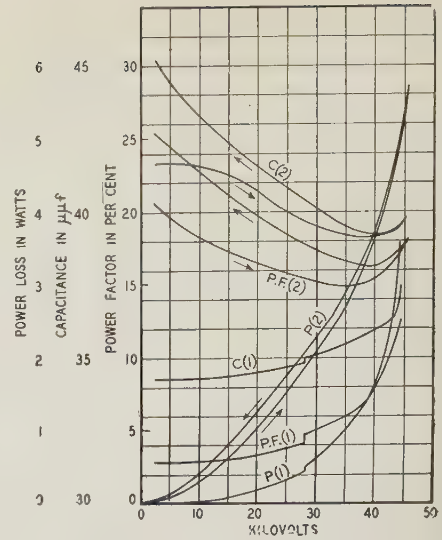


Fig. 1. Variation of power loss, capacitance, and power factor with voltage at 60 cycles

Curves (1) for first trial test; curves (2) after several tests. Tension 400 lb; temperature 21 deg C; relative humidity 75 per cent

In contrast to impregnated-paper cables and similar dielectrics, insulators are composed for the most part of vitreous and other inorganic materials which are usually associated with electrical stability. It was with some surprise, therefore, that we found wide variations in the electrical properties of such insulators with change in voltage, even with little mechanical stress. Moreover, our investigations show that the factors which affect the electrical characteristics are so numerous and difficult to control that they prevent exact duplication of the characteristics in a single specimen even in successive test runs. For example, we find that the characteristics are affected by humidity and by the time of application of the voltage.

In Fig. 1 power loss, power factor, and capacitance are plotted as functions of voltage with a constant value of stress of only 400 lb. In test (2) the voltage was carried to its maximum value and then was gradually reduced to zero. The tests designated by (1) were the initial tests made on the insulator. Those marked (2) were made after 7 cyclic applications of voltage over a period of 2 weeks. It will be noted that the power factor of the porcelain insulator varies widely with voltage and also that it reaches high values. For example, the power factor goes as high as from 15 to 20 per cent, whereas at ordi-

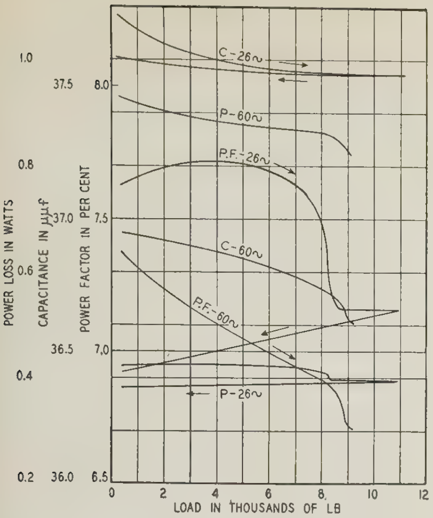


Fig. 2. Variation of power loss, capacitance, and power factor with mechanical load

Tests made at 30 kv and with frequencies of 26 and 60 cycles; temperature 19 deg C; relative humidity 50 per cent

nary temperatures the power factor of impregnated-paper cables is of the order of 0.5 per cent or less. Also, these values of power factor are very much higher than those for porcelain bushings in good condition. The slight abrupt increase in the electrical quantities in (1) occurring at 28 kv is due to the power being interrupted for 15 minutes. The increase in power factor and capacitance with voltage is undoubtedly due in part to corona formation on the hardware, particularly at the edges of the cap.

The characteristics designated by (2), taken after 7 cyclic applications of voltage, are quite different from those designated as (1). The power loss has more than doubled. The capacitance has increased substantially, and now decreases with increase in voltage except near the highest values of voltage. The initial value of power factor is 20 per cent and it decreases with increase in voltage until at 40 kv it begins to increase. The increase at 40 kv in both the capacitance and the power factor are undoubtedly due to corona formation at the edges of the cap. As the voltage is decreased the power loss, the power factor, and the capacitance are all substantially greater than with increasing values of voltage.

In Fig. 2 the effects of mechanical stress are shown. The voltage was held constant at 30 kv and tests were made at 26 and 60 cycles. With 26 cycles a cycle of stress is shown, the stress being increased to 11,000 lb and then decreased to zero. The electrical quantities are all less for the return portion of the cycle. The sudden and large decrease in power factor at 9,000 lb is undoubtedly due to some readjustment of the pin, the cement, and the compound used for sealing. In Fig. 2 the origin is not shown, so that the proportionate variations are not as large as they may appear at first sight. The 60-cycle power loss is considerably greater than the 26-cycle power loss, but the power factor and the capacitance are greater for 26 cycles.

These results are submitted to indicate the direction which our research is taking, and also to show in a preliminary way the effects of voltage and mechanical stress on the electrical characteristics. At the moment it is not possible to analyze and evaluate the different effects shown in these figures, although investigations now being made will undoubtedly make this possible. For example, a graphite guard ring around the porcelain, which interrupts surface leakage, has a marked effect on the characteristics.

In the near future it is planned to publish our results more comprehensively together with theories to explain the characteristics. We also find considerable difference between the characteristics of porcelain and glass insulators. These power frequency characteristics may have little or no bearing on the usefulness of such insulators in service, but the more that we know about a piece of apparatus the better we understand it, and we are in a better position to analyze its operation.

W. A. Hillebrand: The group of papers presented at this session is evidence that the design of a cap-and-pin insulator is an engineering problem and as such may be solved in more than one way. The final test is that of service, but sufficient time has not yet elapsed to demonstrate conclusively the superiority of any one design under average conditions of use.

The constituent materials are portland cement or "type metal" alloy, porcelain, steel, and malleable iron. The elastic properties, temperature coefficients of expansion, and ultimate strengths of these materials differ widely from one another and will vary with composition and method of manufacture. The most critical element is the porcelain, whose mechanical integrity must be maintained, and the entire assembly must be designed for this. The most important requirement is that the properties of the respective materials shall be compatible with the design adopted, otherwise the apparently contradictory results reported by different investigators are to be expected.

Cement and porcelain are used principally in compression and shear, but within the insulator head it is impossible to impose a compression load without setting up shearing stresses in the areas bounding that to which the load is applied, and it is the writer's belief that ultimate failure of the material generally occurs along the shear surfaces. Therefore, criticism of a design that deliberately utilizes cement and porcelain in shear is not necessarily sound. Furthermore, a bursting stress in the interior of a tube, like the insulator head, is accompanied by tension stresses in the tube wall if the slightest movement occurs. This movement is prevented by the use of a heavy-walled cap, whose contraction in cold weather may shear off the flange of lightly loaded insulators in suspension position. This has been observed to a limited extent in suspension insulators, and to a much greater degree in the larger station pillars.

It is not the writer's purpose to condemn any particular design but to call attention to the fact that, as always, a compromise must be made. The most effective use of material that will meet test requirements and produce maximum life is yet to be determined and the designer should still be left a free rein in the solution of his problem.

The longest lived insulators have been those designed for low ultimates and, particularly, for low thermal stresses. Emphasis on long time, high load tests results in thicker metal parts with probably increased thermal stresses. Whether or not these have been pushed to the danger limit we do not know, but it is probable that this feature can be stressed to the point where insulator life will be shortened as a result of the "doughnutting" previously referred to.

The relation of the elastic modulus to the ultimate strength of typical porcelain is such that the ultimate strength is reached with a yield of the order of 0.1 per cent. The wall thickness of the cap-and-pin insulator is 1 in. or less so that the material may be ruptured with a total deformation of not over 0.001 in. This is the order of dimension within which the designer must work. Instruments for measuring deflections under load or temperature change should read to at least 0.0001 in. and preferably to one-tenth of that value. Equipment of this type is difficult to construct and involves elaborate compensation for deflection of supporting members. However, measurements of this refinement are essential for a real understanding of how the component parts of a given assembly behave.

Because of the smallness of deflection that occurs up to failure, the configuration of parts becomes of vital importance. The effectiveness of a given design may be materially altered by a change in the shape of cap, pin, or porcelain. Therefore, whenever such a change is made, the unit should be given a new catalogue or identification number. Otherwise, important and carefully compiled life records such as those submitted by Messrs. Sporn, Peterson, and Mulford lose much of their value because of the impossibility of distinguishing in later years among insulators that are really different.

Professor Dawes has referred to tests of dielectric loss and power factor of suspension insulators. He eliminates surface losses by means of guard rings, but, unfortunately, one of the most important elements is the cement, which is a poor insulator or a semiconductor. Is it possible to separately determine the losses in cement and porcelain? In any event, as a contribution to our knowledge of the subject, his results will be of great interest and may possess a significance that as yet we cannot assign.

One of the most important properties of glass, including insulator glaze, is the adsorption of water vapor in a surface layer of the order of 250 molecules thick. This subject and that of the surface resistance of glass have been most exhaustively studied by the Bell Telephone Laboratories, and in the *Bell Laboratories Record* for October 1933, Mr. Yager gives much significant data. This layer will change in thickness with atmospheric humidity, usually with a time lag of many hours. With it surface resistance changes over wide limits. It is probably responsible for the tenacious retention of space charges which we know may persist for minutes. Because of its effect upon resistance and space charge, it also is probably an important factor in determining the degree of radio influence. Its influence upon dry flashover has been brought prominently to the attention of

engineers in recent years. The following test will serve to illustrate how markedly a porcelain insulator, as a gap, differs from other gaps because of its surface properties. Five successive flashovers were taken at 1-min intervals on a sphere gap, needle gap, and insulator, respectively, all having approximately the same flashover voltage. The differences between maximum and minimum values for each of the 3 were:

Sphere gap	0.3 per cent
Needle gap	3.0 per cent
Insulator	15.0 per cent

In 5 successive flashovers 1 min apart of a suspension disk, I have seen each arc take a separate path at widely separated points around the circumference. In each case the arc cleaned up its path, leaving it of higher resistance to breakdown.

The reason for dwelling upon the peculiar properties of glass surfaces is that they are extremely important in some cases in determining insulator performance, and yet their influence is too often overlooked.

The insulator subcommittee and the several authors are to be congratulated upon the symposium presented. Although apparently a simple structure, the distribution of stresses within the suspension insulator is extremely complex. Add to this the very small displacements that occur up to failure and it is possible to understand how painfully slow and difficult it is to learn intimately and accurately what is taking place. The papers presented contribute to our knowledge and are a step toward the ultimate goal of learning what maximum and working loads may safely be developed in roughly 10 lb of porcelain, malleable iron, steel, and cement.

High Voltage Insulators

Discussion and author's closure of a paper by W. A. Smith and J. T. Lusignan, Jr., published in the June 1934 issue, p. 895–8, and presented for oral discussion at the insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

W. A. Hillebrand: This paper is welcome because the authors call attention to many factors of vital importance in the production of a successful insulator that have not hitherto been stressed and which often tend to be overlooked.

K. A. Hawley: We heartily concur in the manufacturing goal set in this paper. We regret, however, that there is within it practically no information about insulator developments in design or supporting data.

Our experience in making short wave impulse tests does not indicate that the voltages obtained are proportional to the leakage distances. The factors are considerably more complex than this. Our experience indicates that it depends partly upon tight string distance and partly only upon leakage distance.

Electric needles starting from electrodes separated solely by porcelain travel outward because of the high flux concentration at their point until corrugations introduce air gaps between their ends, then for a ways these needles will jump clear of the porcelain surface.

W. A. Smith: Regarding Mr. Hawley's criticism of our use of the leakage distance relationship in comparing breakdown voltages at short time lags, obviously we do not mean that every increase in leakage distance will increase the flashover voltage. However, such factors as increased diameters and additional petticoats of normal shapes will raise the impulse flashover voltages at short time lags more than the increase in striking distance and much more in proportion to the increase in leakage distance. Extremely deep petticoats help little in increasing the breakdown voltage, but an examination of insulators and bushings of the usual designs show discharge marks well into the petticoats and corrugations after applied waves which have caused breakdowns within a few microseconds, indicating that the leakage distances rather than the striking distances have been the important factor.

Mr. Hawley expresses regret that in our paper there is "practically no information about insulator developments in design or supporting data." This paper was not intended as a detailed discussion but as a general outline of certain phases of insulator manufacturing. Details of design and relative data belong to a separate paper and may be presented at some later date.

The Suspension Insulator

Discussion and author's closure of a paper by K. A. Hawley published in the June 1934 issue, p. 895–8, and presented for oral discussion at the insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

W. A. Hillebrand: The papers by Messrs. Barrow and Hawley and the comments that follow will illustrate the extent to which conflicting results may be obtained by different workers in the same field. With much of Mr. Hawley's thesis we agree, but wish to take exception to some of his statements which otherwise might be accepted as of general application.

Through the application of methods that are quite similar, competitive designers have been able to obtain short and long term strengths that, for a given amount of material, are much the same. On the other hand, competitive designs do not in all respects produce similar results.

Under certain conditions glazing over the sand will increase the strength of an insulator, but we have been able to obtain values just as high with sand not glazed over but with a successful combination of glaze and carefully selected sand having grains of proper size for the glaze used. Glazing over the sand is objectionable in that it makes it practically impossible to produce resiliency in the joint by coating the sanded surface, a practice that seems to have been fully justified by its application to millions of insulators during the past 17 years.

Again, some designs will show an increase in strength with age whereas others will not. In Table II of the paper the increase between 18 and 28 days is altogether in the combined electrical and mechanical strength, but not in the ultimate, indicating an apparent ability of the older cement to better distribute stresses, although the average at which it let go seems not to have altered.

On p. 897 the statement is made that insulators have failed because of the use of a relatively large amount of cement in the pin hole. Is this assumed to be because of cement expansion or because of localization of mechanical stresses? In all my experience, with the one exception of a lot of 60-kv pin type insulators in which the pins had been cemented in the field by filling much of the center shell with a very dry cement, I have not found an instance of insulator failure which could be definitely attributed to cement expansion. Does the author's experience conform to this?

On p. 896 failure is referred to as occurring at the boundary of the sand layer. Was this also the end of the glaze coat? In common with others, we find the strength of porcelain appreciably affected by the glaze.

Among improvements referred to is that of the straight pin hole. There has never been any difficulty in manufacturing straight pin holes in so far as the manipulation of the clay is concerned. The taper has been set by practical limitations in the manufacture of blocks and molds.

On the effect of pin eccentricity in lowering mechanical strength, many of our organization are in agreement. Nevertheless, a lot of insulators in which the pins were purposely assembled with their axes at the maximum possible angle with that of the pin hole showed remarkably little variation in the mechanical strength at electrical failure. This leads to the conclusion that the effect of eccentricity is largely determined by design, manufacturing tolerances, and whether or not caps and pin are coaxial, regardless of how the porcelain may be assembled with respect to either.

Again, the statement is made that cement and porcelain have the same modulus of elasticity. This must be true only for the particular materials referred to by Mr. Hawley. In our experience the values for the 2 are not the same.

K. A. Hawley: Mr. Withington has called our attention to the need of rating suspension insulators by their combined mechanical and electrical strengths. Our A.I.E.E. Standards No. 41 are written to cover this "M and E" strength. A complete understanding of it involves several separated paragraphs that may well be combined and interpreted. At present they are somewhat confusing. The present strength ratings in the catalogues are based solely on the mechanical and electrical value.

We have found that the long time ratings are but little below those obtained by quick tests. The margin is not so great as with most other structural materials. We therefore do not understand Mr. Withington's statement that they are much less. Testing for 2 years in an outdoor frame where there have been an unusual number of freezing-thawing cycles and at practically the strength rating of the insulator appears to us to be fully equal to use over a longer period at a much less load. This appears

to us to be the only somewhat accelerated test that we can run that surely uses most of nature's tricks. We are very doubtful of the true value of highly accelerated loaded thermal shocks. Nature has not done those things upon insulators that have broken in service.

In our own experience we hesitate to say that vibration is a major contributing factor in insulator aging. There is no laboratory so well equipped as the transmission line or catenary system for such tests. When there is trouble, coöperation between the manufacturer and user should be had for complete analysis.

Strength tests on every insulator going through the factory are imperative. Routing in production is so arranged that none can escape such tests. While defectives are scarcely ever found, we realize that so long as we are human this is one thing that must not be overlooked.

Some data will be found in the Frey-Hawley paper which is referred to in the current one upon the effect of natural contamination upon insulator surfaces. Mr. Lloyd, in a contemporaneous paper on insulator flashover values, also had similar information. Mr. Withington may find them of interest.

We agree with Mr. Brown that standard tests will not surely eliminate types that may give poor service. It is necessary first to choose those types that have been satisfactory, and then apply tests as Messrs. Sporn, Peterson, and Mulford have done. Where the user has not acquired this experience it is necessary to call upon the maker for references.

Suggestion has been made that scarcely enough insulators were placed in the frames for the conclusions that we have drawn. Those of us who have lived with these tests feel decidedly otherwise after seeing the very satisfactory results.

Mr. Kates has asked if the application of electricity while testing is but an indicator for mechanical failure. We consider it so.

We find that there is little need for a test only slightly slower than that specified in the Standards. We see no need for a combined routine load and electrical test in our manufacture. It is fully as effective to separate them and considerably safer.

The work of Messrs. Dawes and Reiter is very interesting to us. We will make no more comments until their work is published in full and they are able to draw more complete conclusions. Such researches are of real value.

In answer to Mr. Hillebrand's comments, we thoroughly agree that we have not seen failures due to cement expansion where proper and easily available cement has been used. Our experience shows trouble from cement masses caused by contraction, absorption, and freezing, all of which are easily controlled in several ways when the problem has once been understood.

Pin eccentricity in itself does not appear to be a hazard. If, however, it bears against the procelain, there may be trouble. The star washer keeps the pin where it should be and stops any possible trouble.

A slight glaze coating over the sand keeps the sand in place while firing and adds to the strength of the assembly. Factory control easily prevents overfilling between the sand grains to the extent that resilient coatings would be a hazard.

Flashover Voltages of Insulators and Gaps

Discussion of an A.I.E.E. committee report published in the June 1934 issue, p. 882–6, and presented for oral discussion at the insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

C. M. Foust: The progress made within recent months in the securing of accurate impulse flashover voltages of insulators and gaps on the 1 x 5- and $1^1/_2$ x 40-μsec waves is very gratifying. The close agreement among laboratories is unusually encouraging when it is kept in mind that detailed methods of arriving at voltage values and wave shapes were quite varied among the several laboratories.

I would like to call attention to this wide range of measurement methods which includes the following:

1. Measurement of voltage amplitude across the test specimen by direct sphere gap comparison.
2. Measurement of voltage amplitude across the test specimen by preliminary calibration of surge generator output voltage, as indicated by sphere gap against surge generator excitation voltage.
3. Measurement of surge generator discharge circuit constants and calculation of voltage wave shape across the test specimen.
4. Recording of voltage wave shape across the test specimen by oscillograph.
5. Measurement of voltage amplitude and wave shape across the test specimen by oscillograph using voltage divider ratio and oscillograph deflection sensitivity.
6. Measurement of voltage amplitude and wave shape across test specimen by calibration of oscillograph deflection directly against the sphere gap.

All the laboratories which submitted data used either one or some combination of more than one of these methods of measurement and check.

The close agreement among the data submitted by the several groups makes for confidence in the results obtained by each group in spite of the differing methods.

K. A. Hawley: The publication of average flashover data has led to commercial difficulties. Insulator purchasers, not realizing that there are wide variations in flashover values which are caused by things not yet entirely understood, have insisted on writing in their specifications as minimum values the average data given. It is by no means always possible to demonstrate to the visiting inspector these average values, as all who have worked in the laboratories know full well. The help of the Institute's membership to understand that published data are average rather than minima will be greatly appreciated by the manufacturer.

K. B. McEachron: It is significant that a milestone has been reached in connection with the agreement of flashover voltages of insulators and gaps as presented in the committee report. It has taken a relatively long time for the various laboratories to arrive at these agreed upon values, but this is the natural result to be expected from the type of problem involved. Although the 60-cycle test data would seem a logical basis on which first to secure agreement, the paper shows that the impulse values are in better shape today than the 60-cycle values. This is probably due to the very great interest which has developed in the past few years concerning impulse values for insulators and gaps. Agreement will no doubt be reached in the not too distant future for the 60-cycle flashover values, as the laboratories are now busily engaged in securing the necessary data.

Of the various factors which affect the flashover of gaps and insulators, considerable work is still required concerning the effects of air density and humidity. The laboratories are to be congratulated for their work in the past, and we look forward confidently to the extension of the data now available in order that the industry may not be hampered by the lack of knowledge on these flashover values.

J. E. Clem: In connection with the committee report on the flashover of insulators and gaps, it might be interesting to review the work of the laboratory group which is actually carrying on this work.

A few years ago when impulse values came into use, there were great discrepancies among the flashover values emanating from different sources. The differences were in some cases as high as 40 per cent, and it was quite obvious that the industry could not get along with such a situation.

The work was begun by the General Electric and Westinghouse laboratories, joined shortly after by the Ohio Brass Company. Some time later the Locke Company began direct participation, and lately the Allis-Chalmers Company entered the group.

First the impulse flashover values of insulators and gaps were studied, and little progress was made for a long time. As the work progressed, however, minor errors were eliminated and the values steadily came closer. The values for the long wave (1.5 x 40-μsec) were within the tolerance limits set up by the group some time ago, but because those for the short wave (0.5 x 5- or 11 x 5-μsec) were not, it was decided not to make public any values until full agreement was reached. As soon as all the laboratories agreed to use the 1 x 5-μsec wave based on a uniform definition, the main source of differences was eliminated and an agreement soon was reached.

The values agreed upon were given in a report submitted this spring to the joint National Electrical Manufacturers Association-Edison Electric Institute coördination committee. This report covered impulse values only. No agreement has been reached in regard to 60-cycle flashover values.

R. W. Sorensen: It is very interesting to note the progress that has been made by the several outstanding industrial laboratories interested in this program in reaching an agreement as to what are the proper surge voltage flashover values for gaps and insulators. The values as given naturally deal entirely with insulator strings made up wholly of sound units. I have found interest in making some studies of flashover values at power frequency voltages on insulator strings in which some of the units are defective. I think it would be very interesting if some of those laboratories which have surge generators would conduct for us similar tests for surge voltages.

Selection and Performance of Suspension Insulators

Discussion and author's closure of a paper by Philip Sporn, E. L. Peterson, and V. A. Mulford published in the June 1934 issue, p. 936–42, and presented for oral discussion at the insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

K. A. Hawley: An effort at correlating laboratory acceptance tests and field experiences as given by the authors is of real value to all concerned. The form of acceptance tests used by these authors may involve a little longer time than is usual in insulator investigations and purchases. It will, however, be very well indeed to consider the points raised by them in future revisions of the insulator standard specifications. We regret that the authors have apparently not made full use of the manufacturers' advice in examining insulators which have broken. It is largely by examination of defective material that the manufacturer can continue to make improvements.

W. A. Hillebrand: To serve as a basis for purchasing, the authors have established the following test schedule:

1. Time loading test; 6,000 lb for 72 hours.
2. Thermal test of insulators that pass test No. 1; 10 thermal cycles, each consisting of a 10-min immersion in boiling water followed by a 10-min immersion in ice water. During this test half of the insulators are subjected to a load of 3,000 lb.
3. Porosity test; 6 hours in a solution of fuchsine in alcohol at 10,000 lb per sq in. pressure.
4. Electrical and mechanical test; given all units passing tests 1 and 2. Start at 6,000 lb and increase by 500 lb every 30 sec to electrical failure, and continue to complete mechanical failure.

The designer is faced with the double duty of meeting a test specification and at the same time building into the insulator the longest life that he is able to. In their mechanical requirements the authors apparently have not handicapped the design with respect to life. The schedule seems reasonable and it is hoped that it will meet with general adoption, because it is obviously in the interest of economy to have to design an insulator of given rating for but one specification. The following modifications are suggested, for the obvious reason that the maximum loading occurs at reduced temperatures:

The 72-hr loading of paragraph 1 should be at a temperature of 32 deg F.

For the insulators subjected to both the mechanical loading and thermal cycles of paragraph 2, it is suggested that the loading be 1,500 lb during immersion in hot water and 4,500 lb during immersion in cold.

The emphasis on life is welcome and the statement that the useful life of a lot of insulators may have been reached when 15 per cent have failed is a frank recognition of the hazard inherent in the material.

According to Table II of the paper, insulators manufactured through 1927 showed more or less porosity. The actual record must have been largely determined by the method of making tests and of interpreting results, because in our plant any porcelain which would show a penetration of from $^1/_{16}$ to $^1/_8$ in. would allow the dye to go completely through the test piece. In addition to pore space, the dye will penetrate fissures formed in breaking up the test specimens. If the test pieces are not wiped and dried completely after immersion and before breaking to detect penetration, the wet dye will flow around the edges of the freshly broken surfaces. Also, in any porcelain it is possible to find pore spaces which have not been completely filled in the firing, but these are not necessarily a detriment if isolated and of such small proportions that mechanical and electrical strengths are not impaired. Laps are something quite different.

In 1925 committee D-9 of the American Society for Testing Materials started to develop a quantitative test to replace the qualitative dye test. Their work resulted in a method which is based upon the extraction of the air in the samples by placing them in a vacuum over mercury. This test, D-116-30, now replaces the dye test for porosity and is recommended to the insulator subcommittee for consideration.

The results of any test should be based upon the performance of acceptable ware. Electrical porcelain must insulate throughout the full length of its life, but overemphasis on porosity will result in a product that is glassy, overvitrified, and weak mechanically and electrically.

W. A. Kates: On p. 936 of their paper the authors state that the present A.I.E.E. standard tests for suspension insulators are not sufficient to form a basis for detecting insulators of inferior design and manufacture. With this I heartily agree. The irregularities of the oil puncture tests, for example, were pointed out by Drs. Littleton and Shaver of the Corning Glass Works in the September 10, 1927, *Electrical World*, and again in the April 14, 1928, issue of the same journal, some 2 years before adoption of the present standards. It may be easily demonstrated in a short time by anyone with the aid of a testing transformer, oil, insulators, and a few drops of water. Vagaries due to humidity were also pointed out in a companion paper in 1928. Also, it can be readily demonstrated with transparent glass that cracked shells, having visible cracks undetectable by power loss measurements, will satisfactorily withstand either 60-cycle or continuous voltage for 5 minutes, and high frequency tests prolonged for 5 minutes, or to thermal failure of the material in question. An oil puncture test, too, fails to detect such cracks. In Mr. Lapp's paper, paragraph 1, he notes most failures of porcelain insulators are caused by lack of internal soundness, corroborating our experience. Have the authors had similar experience in their tests of porcelain or any indication that service failures are the ultimate result of such initial conditions?

These 2 aforementioned facts excite valid question of the suitability of service records as criterions of design because these service records, consciously or not, assume all insulators to be in perfect condition when installed. Such may or may not have been the case. The failures in service may have been due either to design or manufacture, although to the operating engineer the results of the failure are the same.

The authors note on p. 939 the use of test sticks for field testing. Presumably the data of Table IV and Fig. 2 were obtained from the results of testing with these sticks. Are failures so detected the only ones summarized, and if so, are failures due to other causes such as arcing or mechanical damage believed inconsequential?

There is one factor which is pertinent to this paper but which I do not find stated. That factor is the basis for the implication that inequalities in performance denote corresponding inequalities of merit. Were the units compared all of the same mechanical ultimate rating? Were these ratings assigned by the manufacturer? Were all units intended for the same mechanical loadings in service?

In the second paragraph it is stated that although vast improvements in product have been made, "it does not follow that a uniformity of the product has been reached that will assure satisfactory operating reliability." In 1930 the National Electric Light Association insulator research subcommittee in its preliminary report recommends the expenditure of $15,000 to initiate research of far reaching effect on the suspension type porcelain insulator. The concluding remarks of the authors' paper is that a life expectancy of 50 years is not beyond realization. I would like to ask the authors if this is their present expectancy of suspension insulator life.

Philip Sporn: With regard to Mr. Kates's question on the use of test sticks, the data in Table IV and Fig. 2 were obtained from tests with insulator test sticks, and failures due to arcing or mechanical damage are not summarized. The latter are certainly not inconsequential but the authors do not believe that such failures should be included as they have no bearing on the depreciation of insulators as a whole nor on their life expectancy.

Mr. Kates inquires as to whether the insulators compared were all of the same mechanical strength rating, whether the ratings were assigned by the manufacturer, and if all the units were intended for the same mechanical loadings in service. It is true that some of the insulators tested were of a higher mechanical strength rating than others but most were in the same strength classification. As stated in the paper, the tests were originally designed for insulators to be used on the 132-kv system. The authors do not believe that the loadings are excessive for even the lightest of the units that were under consideration, and in all cases were under the strength ratings as given by the manufacturers. As a matter of record, the higher rated strength units did not always test out the best and in one case the lower strength units of one manufacturer tested better than the higher strength units produced by the same manufacturer.

With regard to the concluding question of Mr. Kates, the authors believe that a 50-year life may be possible with some of the units being manufactured today although they admit that available data are limited.

The authors are pleased to note that some members agree with them that present A.I.E.E. standard tests for suspension insulators could be broadened to advantage to include additional tests which would be of considerable assistance in detecting insulators of inferior design and manufacture.

Radio Influence Insulator Characteristics

Discussion and author's closure of a paper by G. I. Gilchrest published in the June 1934 issue, p. 899–902, and presented for oral discussion at the insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

W. A. Hillebrand: The paper describes an interesting and important method of rendering a porcelain surface conducting and at the same time eliminating the undesirable fringe effect at the edge of the coating. Since the copper oxide used in the glaze can be reduced to metallic copper by the application of an acid of sufficient strength, it is important to know if the glaze will meet the conventional specification that it must be unaffected by acids in the concentrations found in the atmosphere of industrial communities.

All of the radio influence tests were evidently made upon clean and dry insulators in which the voltage distribution is entirely determined by the capacitances of the several insulator shells. When wet, or partially wet, and dirty, surface resistance controls the distribution of voltage, and in an erratic manner. Under these conditions the radio influence characteristics would unquestionably be quite different. This is particularly true of suspension insulators, which, in a gathering fog, may have an appreciable radio influence at voltages as low as 25 per cent of those reported in the table on p. 902.

In coastal and other regions hygroscopic salts such as magnesium chloride from sea water, for instance, which may be present in the atmosphere, will collect on insulator surfaces and modify their behavior to an important degree. Above 60 per cent relative humidity these salts may absorb enough water from the air to reduce the surface resistance to less than 1 per cent of its value when clean. Leakage current is correspondingly increased and the fall of potential caused by this current in passing from tie wire to insulator surface may cause breakdown of the air at this point and corresponding radio influence at a much lower voltage than when the insulator is dry and clean. In one section of the country, the influence level, based upon field measurements, seems to be several times as high when the insulators are dirty as it is after they have been washed by winter rains. This is a condition which apparently no coating as yet proposed can remedy.

The statement that for field application an asphalt emulsion offers the best solution is questioned on the ground of probable carbonization and destruction of this coating by leakage currents in wet weather. A conducting paint that, from several years' experience, seems to be but little affected by weather should give a longer life.

The voltages for minimum radio influence of similar insulators as reported respectively by Mr. Gilchrest and by Mr. Lapp seem to be inconsistent and to further emphasize the necessity for a standard test arrangement for determining the point of breakdown at which the influence becomes apparent.

K. A. Hawley: The de cription given by Mr. Gilchrest of the circuit for determining radio frequency influence has, we believe, been recognized by certain of the joint committees on acoustical relations. The data given by Mr. Gilchrest upon the circuit with varying constants is of real value and may become the basis for standardizing such tests. The results obtained by placing copper coatings upon the tops of pin type insulators appear to be satisfactory providing the coating is permanent. The results obtained are much like those which have been obtained by our company by the use of proper gaps on the insulators and which have been described in ELECTRICAL ENGINEERING.

G. I. Gilchrest: Mr. Hillebrand refers in his discussion to the possible effect of acids found in the atmosphere of industrial communities. Insulators having the copper oxide glaze treatment have been in service under various industrial conditions during the past 3 years. Also, accelerated life tests have been made during our research investigation of the permanency of the coating.

The surface tends to remain copper oxide excepting under acids sufficiently strong to reduce the copper oxide to copper. The developed copper surface must be tinned in order to protect it from the atmosphere, which would normally return the copper to copper oxide. We find the conductivity of the copper oxide glaze is practically the same after 2 or 3 years in the atmosphere of industrial communities as the regular porcelain glaze.

Mr. Hillebrand questions the performance of insulators treated with copper oxide glaze under fog conditions. Many tests have been made with the copper oxide glaze insulators subjected to salt sprays, dust sprays, atomized water sprays, etc., under laboratory conditions. The performance of the insulators treated with copper oxide glaze is substantially the same as the performance of standard insulators with respect to wet and dry flashovers. The copper oxide surface performs the same as the standard glaze surface. The copper oxide glaze treatment is not proposed to eliminate the effect of fog conditions but will definitely improve the performance of the pin type insulator under conditions of dirt and moisture accumulation on the surface, up to the point where static streamers begin to discharge over the insulator surface. Where fog conditions are sufficiently severe to warrant additional leakage surface, special shape of sheds, etc., the copper oxide glaze may also be applied to advantage.

Mr. Hillebrand indicates in his discussion that he believes that a conducting paint should give a longer life than an asphalt emulsion. Doubtless Mr. Hillebrand's assumption is correct. However, in our experimentation, we have found that the metallic painting is not satisfactory because it leaves a metallic edge from which discharges take place. These discharges offset to quite an extent the advantages of the metallic glaze which eliminates the discharges from tie and line wire to porcelain. As explained in the article, the copper oxide glaze treatment entirely eliminates the discharge from the conducting surface because of the grading affect that exists between the metallic surface and the undeveloped copper oxide surface. The asphalt emulsion eliminates the static discharge from line and tie wire to the porcelain and does not give a metallic edge that must be present with metallic painting.

Recent Developments in Suspension Insulators

Discussion and author's closure of a paper by G. M. Barrow published in the June 1934 issue, p. 867–70, and presented for oral discussion at the insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

W. A. Hillebrand: Mr. Barrow's paper is a plea for the one-step bolt or button head pin, the relative merits of which time alone can answer. With his insistence upon the importance of resilience and recovery in the center pin I heartily agree. With the statement that static time loading is the most important test of an insulator I cannot concur. Carried to its ultimate conclusion, it will probably result in too heavy caps and doughnutting. The test is of value only in its relation to the performance of the insulator in other ways, particularly when subjected to extremes of temperature.

The statement that the greatest hazard is where the porcelain envelopes the metal is also open to question, because cap contraction on the practically unloaded insulator in suspension position may, in some instances, be of greater importance. On p. 868 Mr. Barrow states: "It is of interest to note that in experimental assemblies where much slippage of the cap occurred, the bell of the cap was ruptured by splitting; the porcelain was not impaired." May I ask of what material these experimental caps were made? Also, is it probable that caps made of other materials and within practicable manufacturing limits would have acted similarly?

A. E. Davison: The author is to be congratulated upon having made available to engineers representing consumer organizations data regarding the fatigue limits of materials and equipment in which the writer is interested. He also is to be congratulated upon having modernized the testing of equipment associated with transmission line conductors wherein fatigue and failure resulting from vibration are making themselves more and more evident to those responsible for the maintenance of transmission lines having higher mechanical tensions.

Mr. Barrow says: "The results of these (vibration) tests indicate that the porcelain is less susceptible to vibration than the connecting hardware. They also confirm research findings that the fatigue strength of the porcelain is at least 80 per cent of the static strength in comparison to approximately 60 per cent and less for metal."

Data of this nature are desired by consumer engineers and it is hoped that representatives of other supply organizations will either confirm Mr. Barrow's statement regarding conductor materials or supply authoritative data regarding "endurance limits" of the materials and of the fabricated

equipment which they themselves advocate.

Time-load tests are briefly referred to by the author. No reference is made by the author to either "creep" or permanent stretch.

K. A. Hawley: Many of the things pointed out by Mr. Barrow are confirmed in my 1931 paper and by the one in the current issue. The tension and shear type design with its multiple ridges inside of the cap has fully been commented on in the first paper for these upper ridges carry most of the load delivering it well above the keystone of the arch. This insulator, therefore, must not be confused with the multiple stepped insulators described in my current paper.

The objections that we see to the single step bolt need not be repeated for they are also fully covered. A comparison of this design as disclosed in patent 1,822,485 filed in 1924 will be of real interest for in that was fully contemplated the effect of curved steps upon the insulator bolt.

G. M. Barrow: The discussions on the insulator symposium are interesting as they indicate a careful analysis of the subject from several different points of view. A number of references are made relating generally to the present A.I.E.E. standard test specification and specifically to several items of my paper on which I wish to comment. My paper naturally was restricted to insulators of our own design and manufacture. Figure 1*a* of the paper illustrates a tension and shear design, several million of which are in use and giving very good service. Figure 1*b* illustrates a later type of insulator which has been in production for 5 years and is commonly known in the trade as the compression type design. The remarkable improvement in sustained time-load performance of this latter design is given in Table I.

The analogy to the keystone arch and buttress principles of construction for this compression type design has some basis on facts. To illustrate, by cutting slots in the bell of the cap this buttress support is so weakened that the porcelain is permitted to yield sufficiently to cause rupture at a load of approximately 8,000 lb. The normal breaking load is 15,000 lb. Again, by reënforcing the bell of the cap by shrinking a metal ring on to it, and minimizing yield in the porcelain, the breaking load is increased to approximately 20,000 lb. Tensile and shear stresses cannot be eliminated entirely but they are reduced to such a degree that the total load carried for a long period of time is greatly increased.

Such reënforcing of the cap adds considerable weight and is not justified economically. It may also produce shear stresses that would cause the "doughnutting" Mr. Hillebrand mentions. The cap on the compression type design is of the approximate thickness of the former shear type. The caps that split without impairing the porcelain were made of malleable iron. Measurements of cap yield under insulator load have been made on both malleable iron and forged steel caps, and the results demonstrate that the caps approach the elastic limit at high loads when slipping occurs. Experience with the shear type design and these data indicate that the cap on the compression type design need not introduce any new hazard. Having equalized the other factors, the design of the pin with respect to the stress distribution and behavior under load and temperature changes remains the important factor in the assembly.

I believe Mr. Hillebrand's comment on the importance I attach to static time loading, that "carried to its ultimate conclusion it will probably result in too heavy caps and doughnutting," points out one of the features which would limit such a conclusion and which would force the use of a less heavy cap to obtain the optimum on time-load. This point illustrates the balance of the several factors in the assembly relating to stress from static loading and thermal changes that is required to get the most out of it and maintain the mechanical integrity of the porcelain.

The time-load test with or without thermal changes undoubtedly offers a good criterion of comparison, as may be seen from Mr. Sorensen's paper on such tests in the August issue of Electrical Engineering, p. 1221–4. A design that does not show a satisfactory performance on a test such as his cannot be expected to show to better advantage when also subjected to combined load and thermal changes. Conversely, a design that shows the best performance on static load test without thermal changes may not necessarily show the best performance under combined load and thermal stresses.

Many of these new developments originated since the A.I.E.E. Standards No. 41 on insulators were issued and last revised. and no doubt some recognition and adoption of them will be taken in the next revision. After the time-load performance over a period of 2 years or longer is determined, it might be checked by a test of 1 or 2 weeks if proper differential in load is made. A time-load test of such short duration may disclose a comparatively poor design but I doubt that it would be sufficient to determine the best one. The time-load test through several seasons of normal weather and temperature changes may, I believe, be taken as an indication that the compression type design will take care of thermal changes, considered on the basis that the shear type design did not under similar load and thermal changes. The A.I.E.E. 20-minute immersion cycle thermal test over a range of 166 deg F is largely in the nature of a heat shock test on the assembly and gives practically no information on the ability of a design to withstand a 48-hour cycle time-load thermal test over a range of 140 deg F, with a lower temperature limit. It would not be expected, however, that a design that does not meet the A.I.E.E. 20-minute test would pass the 48-hour time-load test. Electrical failure on time-load test of otherwise dielectrically sound porcelain I consider to be the confirmation of a mechanical fracture. The 3-second axial pull at 40 per cent of rated strength (A.I.E.E. Standards 41-301) is considered a check only on the workmanship of assembly and not as a test on the soundness of the dielectric or the ability of the design to withstand stress. Mr. Kates mentions the use of a 5-minute test on glass insulators instead of the 3-second test as a better indication of satisfactory uniform product. This indicates questionable workmanship or susceptibility to injury in assembly and weakness in combined mechanical-electrical strength. This latter is a design characteristic, the check on which should not be combined with factory routine proof tests.

A New Porcelain Post Insulator

Discussion and author's closure of a paper by G. W. Lapp published in the June 1934 issue, p. 922–5, and presented for oral discussion at the insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

W. A. Hillebrand: Mr. Lapp has developed an insulator which, under most conditions, will have much less radio influence at rated voltage than will the conventional pin type designs. The emphasis on low electrostatic capacity is believed to be sound and in many situations the employment of an insulator utilizing this principle may be the only practicable solution.

However, the reliability of the conventional single and multipart designs has been established through 40 years of service and they should not be discarded until the new insulator, in sufficient quantity, has demonstrated its ability to meet the objections which experience and reason will raise.

The insulator is not new, having been in use as a station post or pillar for over 20 years. In limited quantities it has been used for outdoor service, but became discredited due to the tendency for the head to crack off from the heat of a power arcover. Although insulators of this type inherently develop great strength as a cantilever, their resistance to mechanical shock is low because of rigidity and complete lack of resilience. Its ability to withstand the shock of an automobile colliding with the pole is yet to be determined.

Accordingly, the great danger with this insulator is that of dropping the conductor in case the insulator is broken, although this is to some extent minimized by the fact that the conductor is carried above and not below the cross arm. This danger is aggravated by the fact that the particular usefulness of this insulator is on lines running along highways and through cities, towns, and villages.

Another source of breakage is in the contraction of the metal base upon the porcelain in cold weather. Such insulators have not been free from internal sweating in the past and condensation on the inner wall increases the danger of puncture by lightning. The insulator has a low wet flashover voltage. When a dirty unit of this type is wetted by a fog or drizzle the head will tend to dry more rapidly under the leakage losses, with complete voltage unbalance and probable radio interference at this time.

A few scattered comments on statements made by the author follow. The statement is made that failures of pin type insulators have been due to lack of internal soundness. We have generally attributed them to poor design, poor assembly, or to a combination of the 2. It is inferred that the shells of multipart insulators will carry

cracks, once started, into the body of the porcelain. Judging from observation of many insulators that have cracked in service, aging cracks start in the inner part of the porcelain and work outward, rarely progressing in the opposite direction, unless caused by a blow. The shells that are so severely criticized are valuable for many reasons. They furnish wet and dry flashover resistance, leakage resistance, and act in a valuable way as radiating fins that conduct heat to and from the center of the insulator, tending to equalize temperatures throughout. The annular flanges on the new post type insulator do not add strength to it as a cantilever in the direction where strength is most needed.

J. C. Rah: Referring to this paper, it is interesting to note that the post type of insulator is coming into prominence again after having been practically abandoned for many years. I believe that an insulator of this type has greater possibilities in its field than any other type, as it can be adapted more easily for various purposes. Because of the flexibility of its design, which makes it easier to treat theoretically and to produce commercially, such an insulator may approach more closely to the electrical and mechanical characteristics of an ideal insulator. That an insulator of this type can be more universally used is shown by the example of bushings designed in a somewhat similar manner in which proper arrangement of capacities can be obtained more readily than with any other type using few and large petticoats.

However, I would like to mention one point that the author makes on p. 925, at the end of the second paragraph, under the subtitle, "Electrical Characteristics," in which he says: "The internal air path is a region of negligible dielectric stress." From my experience I have found that one of the most important reasons why such a post type insulator has been practically abandoned during the past few years is that the dielectric stress in this internal region is of real importance. In a closed up air space inside of an insulator, ozone is generated under electric stress and eventually nitric acid is produced which, in one way or another, will cut down the useful life of the insulator assembly. In corroboration of this statement, there was a short notice in one of the issues of the *Electrical World* about 8 years ago, which reported a case of nitric acid damage to an air break switch that was mounted on post insulators of a type similar to that described in this paper.

May I suggest that, in order to get all the benefits from the advantages of this type of insulator, it would be advisable to fill up the internal space with an insulating material of a higher dielectric constant than air, and as near to the dielectric constant of porcelain as possible.

This insulator is an excellent example of how radio interference may be reduced in its effect by design only, without any additional remedial procedures.

R. W. Sorensen: The insulator described by Mr. Lapp in his paper has many desirable features, but its design suggests to me some undesirable ones; not the least of which is the difficulty of greatly reduced flashover voltage in foggy and rainy weather because of the closeness of the petticoats. That is, is there not a probability of a heavy flow of water down over the petticoats when they are so close together, such as to produce a fairly continuous stream which would be conducive to a low arcover voltage? I would therefore, like to have Mr. Lapp discuss this particular phase of his insulator.

K. A. Hawley: Mr. Lapp has endeavored to overcome radio interference trouble in pin type insulators by working in the opposite direction from other investigators such as Mr. G. I. Gilchrest in his current paper and by ourselves with capped insulators.

In decreasing the electrostatic flux he has tried to eliminate the cause of the trouble, while in shorting out air gaps we have stopped the trouble in a different way. Mr. Lapp has established a factor, L/CP, which gives the measure of flux concentration of the tie wire. This factor no doubt has some merit in comparing insulators such as shown in his article. However, it leads to absolutely wrong conclusions when comparing the coated top or insert type insulators.

In determining the radio interference point they have used a radio set loosely coupled with the insulator under test, separating the antenna from the conductor by about 4 ft. Tests made in our laboratory indicate that separation even by this short distance will raise measurably the radio interference point. It would have been much better to have used a circuit like that described by Mr. Gilchrest.

The Lapp post type insulator with special recessed head appears very fragile and probably will be easily broken by hunters or by stone throwing.

G. W. Lapp: Dr. Sorensen inquired if there is a radio effect due to cascading water drops between corrugations of the porcelain post insulator. This is a pertinent question. Under some conditions there is a certain characteristic little banging sound from this cause distinct from the frying sound of ordinary corona or static. This sound is minimized in service by the fact that the sparklets between falling drops are shunted by the short wet surfaces between corrugations. Such wetting of the recessed surfaces is encouraged by the ready access of drifting fog or spattering of rain up under these relatively short petticoats. In several years actual experience with this type of closely spaced corrugations, interference of this character has not been reported.

Mr. Hillebrand, Mr. Hawley, and others discuss a number of points:

1. Sensitivity of receiver for laboratory tests may be neglected since radio effects on a dry insulator start at a critically sharp voltage value which is the minimum for initial effect and is identified as the point of initial corona.

2. Mechanical reliability has been established by shooting tests and by blows with hammers and falling weights. The corrugations do run around and although they add nothing to cantilever strength, they prevent a crushing blow from cracking the body of the insulator. Cantilever strength can be designed to specification. The problem of pinch-off at the base is taken care of by providing adequate distance and easy radius of curvature between the lip of the base and the first corrugation. There is not present an opportunity for concentration of impingement and shear comparable to the head of an ordinary switch type having a large radially rigid shell adjacent to a metallic lip.

3. In the statement that lack of "internal soundness" has caused most insulator failures, it is meant to include assembly of the insulator parts as well as the inherent quality of the parts themselves.

4. Low wet flashover does not seem to mean flashover in service. In fact this type of corrugated leakage path provides improved freedom from flashover under extreme conditions of dirt and moisture to such a degree that it brings into question the established criterion of wet flashover as an all important factor. Increased length of leakage path having characteristics of relatively uniform width and uniform wetness and dirtiness enables this insulator to discourage flashovers through the usual switching and impulse surges. The observation in the oral discussion of J. T. Lusignan that impulse flashover seems to be a function of leakage distance is confirmed to a degree by experience with this insulator as conditioned in actual service.

Mr. Rah brings up my statement that "The internal air path is a region of negligible dielectric stress," and mentions the formation of acid-forming ozone in the hollow space. This subject has been given careful consideration; not so much from the point of view of avoidance of puncture, but more especially to avoid that small degree of conductivity that might cause radio disturbance. The hole at the bottom is effectively plugged by a combination metal-core rubber-capped plug forced into the hole, followed by asphalt coating, and cement-backed at the time the metal base is cemented on. Before plugging the hole the air is scavenged out with a blast of carbon dioxide, thus eliminating moisture, nitrogen, and oxygen, all of which would be necessary to form nitric acid. This inert gas is confined under considerable pressure. The rubber plug is of very stable quality not in contact with oxygen, light, or active dielectric field. Since moisture is absent or of very low content in the inside atmosphere of the fire-clean porcelain hole it is expected that not even high resistance condensation will deposit on the inner wall. If the dew point is below freezing moisture conductivity will be absent or negligible. To give full assurance against puncture and indicate performance, impulse flashover tests were applied to a 66-kv porcelain post insulator. Tests were made dry, wet, and lastly wetted outside and inside with tap water of low resistance. Many impulse shots showed no puncture, no decrease in flashover voltage wet, and no tendency for the spark to follow the outside leakage surface of the insulator even when the hole was thoroughly wetted. The only case of blow-up we know about on switches was due to deterioration of poorly applied plugs in the top of tubular posts. It should be understood that these posts have solid porcelain closed tops.

The statement that the upper end of the hole is a region of negligible dielectric stress is indicated by the fact that the concentration of stress under the tie wire is not sufficient to cause corona at duty voltage, and the diffused gradient inside the hole is of course much less than the gradient at contact outside. There is no visible corona at the top of the hole at flashover voltage as shown by looking through an open hole in the base in the dark.

If the hole were filled with material of higher dielectric constant as Mr. Rah suggests, it would increase the capacitance of the insulator and also create a problem of volume expansion and contraction which happily does not exist.

News

Of Institute and Related Activities

The Institute Budget for 1934–35

EARLY in the present year Mr. E. B. Meyer, then chairman of the finance committee of the Institute, furnished to the membership in the columns of ELECTRICAL ENGINEERING (March 1934, p. 375–81) a presentation of facts and figures relating to the annual budget. While it has always been the practice to include in the annual report of the board of directors to the membership a detailed statement of financial operations for the corresponding fiscal year, it was felt that the exigency of the times warranted a more thorough explanation of some of the problems as they have been presented to the board of directors, together with a brief outline of the steps toward solution, as taken by the finance committee.

Almost concurrently, President J. Allen Johnson, then vice president of the Institute, delivered an address on the subject "An Insight Into the Workings of the Institute" before a meeting of the North Eastern District held in Worcester, Mass., May 16–18, 1934. Essentially the full text of this address was printed in the July 1934 issue of ELECTRICAL ENGINEERING, p. 1039–46.

An opportunity has thus been afforded to the membership to become better informed regarding the organization and activities of the Institute and the nature and relative importance of the various items that make up the annual budget. With the purpose of showing the extent of study and consideration given to the subject, the article on the budget included particularly an explanation of the expenditures for those activities considered by the board of directors and the finance committee to be of major interest to the greatest number of members. For comparison purposes, and also to show the curtailments effected during the period to bring expenditures within the limitations of expected income, the article contained a statement of expenditures for the appropriation year ending September 30, 1931, and also a statement of the anticipated expenses for the year ending September 30, 1934.

The finance committee feels that the membership will now be equally interested to receive a report of the actual income and expenditures for the appropriation year which ended September 30, 1934, together with a statement of the estimates for the present year, with comments on the expense budget to indicate any material departure from the policies already explained by Mr. Meyer and in effect during the past year. Figures for the last appropriation year and estimates for the present year are given in Table I.

PUBLICATIONS

ELECTRICAL ENGINEERING. The unified publication plan which has been in effect since January 1934 has enabled the Institute to supply its members and enrolled Students with virtually twice the amount of technical material formerly published and at a greatly reduced unit cost. The budget provides for the publication of the same amount of technical papers and discussions as was contemplated in the adoption of the 1933–34 budget and also takes into consideration a moderate increase in printers' charges which becomes effective in January 1935.

TRANSACTIONS. Upon publication of the December 1934 issue of ELECTRICAL ENGINEERING, approximately 1,900 pages of technical material will become available for publication of the 1934 annual volume of TRANSACTIONS, to be distributed to members and others who have already authorized the subscription charge for this volume. The budget covers not only the expense involved for the completion and distribution of the book, but also provides an allowance for printing the text pages of the January to September issues of ELECTRICAL ENGINEERING which will be included in the succeeding volume.

YEAR BOOK. In the effort to allocate as much as possible of the expected income to those activities which are of the greatest interest and benefit to the membership, it was decided to omit any appropriation for the publication of another edition of the Institute YEAR BOOK in 1935; the necessary appropriation is included, however, to maintain the current records. A good supply of copies of the 1934 YEAR BOOK remains on hand, for distribution to members upon request.

INSTITUTE MEETINGS

The appropriation for meetings to be held during 1934–35 has been estimated to conform with the expenses of the past year for the 3 annual national conventions, and also to include an allowance for meetings in Districts Nos. 5 and 7, provided for in the 1935 meetings schedule.

INSTITUTE SECTIONS

Practically all of the Sections of the Institute accepted the invitation of the board of directors to make voluntary reductions of 20 per cent in the maximum amounts of their appropriations for the year ending September 30, 1934, as determined under the by-laws. It has been the desire at all times to support Institute Sections as liberally as circumstances would permit, and although there have been no evidences that the work of Sections on the whole has been seriously handicapped by the reduced appropriations (to the contrary, some Sections have voluntarily refunded an additional portion of their appropriations, and others show unexpended balances), the board of directors is inviting the Sections this year to accept voluntary reductions of 10 per cent, rather than 20 per cent, of the maximum annual appropriations, and thus contribute to the effort to allocate equitably the anticipated income to the various activities planned for the year.

INSTITUTE BRANCHES

To allow for an increase in the expenses of Branch meetings, as indicated by expenses reported for last year, the appropriation for this purpose has been slightly increased. The appropriation for traveling expenses incidental to the District conferences on Student activities has been maintained at the same amount as last year, an increase in the number of such conferences being anticipated. In addition to the allowance for representation by the counselor and the incoming Student chairman of each Branch within the District (alternates not authorized) an allowance has now been made for the traveling expenses of the District secretary to the annual District conference. The appropriation again provides for a combined conference in Districts 8 and 9, and makes the usual allowance for traveling expenses for the conference of counselor-delegates to the 1935 summer convention.

ADMINISTRATION

The appropriation of the administrative department absorbs the full salary of the national secretary and the office manager, and 41 per cent of the total of salaries paid to 20 other members of headquarters' staff (the smallest staff per 1,000 members of any of the Founder Societies). At the recommendation of the finance committee, the board of directors voted to restore a portion of the headquarters' staff salary reduction effected in June 1932, to the extent of 5 per cent of the salaries now being paid.

Other items in this appropriation are provided for to the same extent as last year: expenditures for postage, printing, telephone service, telegrams, insurance, cartage of mail, express shipments, engrossing diplomas, check tax, bank collection charges, miscellaneous office supplies, and headquarters' expenses.

TRAVELING EXPENSES—GENERAL

Under this classification are shown the traveling expense allowances for the meetings of the board of directors and executive committee, the annual meeting of the national nominating committee, the visits of the vice presidents to the Branches and Sections within their Districts, and the annual meetings of the geographical District executive committees. For the latter

meeting the appropriation provides for the allowance for traveling expenses for the vice president, the District secretary, either the chairman or the secretary of each Section within a District, and (in accordance with recent approval by the board of directors) the chairman of the District committee on Student activities.

Other Activities

The remainder of the budget comprises those items for which further explanations, beyond the statement of the appropriation or activity, the amount expended last year, and the estimate for the present year, probably are unnecessary. Mention should be made, however, that the appropriation for American Engineering Council has been increased by $3,000 (appropriation for calendar year 1934 being $6,000) with the expectation that the other member societies will proportionately increase the amount of financial support for the year beginning January 1, 1935. Similarly, the board of directors authorized an additional allowance of $1,000 in the appropriation of Engineering Societies Employment Service for the particular purpose of sharing, with the other Founder Societies, the estimated salary and clerical expenses for a representative of the employment service in Washington. The proposed increases in these appropriations are, therefore, conditional upon approval by the other societies of their respective shares of the total appropriations estimated.

It is the intention of the finance committee to report more in detail regarding the various aspects of these and other appropriations in the columns of future issues of Electrical Engineering.

In formulating the expense budget for the present year, the board of directors and finance committee have endeavored to give the various phases of Institute life the degree of emphasis which each deserves. The estimate of income to be received during the year, of which the major portion is derived from membership dues, is predicated upon a continuance by each member of his active interest in the general and financial welfare of the Institute, as evidenced in the results of budget operations for the appropriation year which ended September 30, 1934. In this connection it would seem most appropriate to quote the closing remarks of J. Allen Johnson on the occasion of his address at Worcester:

"......the Institute seems to reveal that its aims and activities are rooted in a spirit of mutual helpfulness to each other and disinterested service to humanity. Its officers, its headquarters staff, and those who work on its committees all share in that spirit. The principal obligation of membership, it seems, is to cultivate that spirit, the possession of which, after all is said and done, yields the most lasting satisfactions of the professional life."

Table I—Institute Expenses and Income for Year Ending September 30, 1934, and Budget for Year Ending September 30, 1935

	Actual Expenses and Income Year Ending 9/30/34	Budget for Year Ending 9/30/35
Expenses		
Publications		
Text matter	$70,379.76	$68,650.00
Advertising section	10,671.64	10,625.00
Year Book	6,008.26	2,450.00
Institute meetings	9,399.09	10,900.00
Institute Sections		
Appropriations	16,443.77	18,132.00
Trav. exp. convention delegates	2,962.35	3,100.00
Other expenses	4,691.64	5,000.00
Institute Branches		
Meetings expenses	967.15	1,000.00
Trav. exp. District conferences on Student activities	2,797.16	4,550.00
Other expenses	1,363.17	1,525.00
Administration		
Headquarters salaries	29,714.18	31,250.00
General (postage, printing supplies, etc.)	11,058.32	11,500.00
Membership committee	6,055.78	6,850.00
Traveling exp. general		
Board of directors	2,369.90	3,250.00
Geographical Dists.	1,355.42	1,800.00
Nat. nominating com.	1,207.90	1,250.00
United Engg. Trustees		
Building assessment	2,966.40	3,000.00
Engineering Societies Library	7,345.38	8,566.00
Engineering Societies Employment Service	2,954.79	*3,700.00
American Engg. Council	7,625.00	*9,000.00
Standards committee	4,655.00	6,200.00
Other committees and miscellaneous expenses	11,705.92	10,302.00
	$214,697.98	
Excess of income over disbursements	19,831.22	
Total	$234,529.20	$222,600.00
Income		
Dues	$168,398.60	$155,750.00
Students' fees	8,604.50	8,500.00
Entrance fees	3,654.00	3,500.00
Transfer fees	875.00	800.00
Advertising	22,842.85	20,000.00
Elec. Engg.—non-member subscriptions	11,278.37	11,000.00
Trans. subscriptions	4,015.82	4,500.00
Miscellaneous sales	5,681.83	5,000.00
Revenue from badges	1,184.40	1,250.00
Interest on securities	7,993.83	8,000.00
Excess of estimated expenses over est. income		*4,300.00
Total	$234,529.20	$222,600.00

* As explained in notes, appropriation increases totaling $4,000.00 were authorized by board of directors conditional upon corresponding increases in the financial support of joint activities by the other Founder Societies concerned.

The Institute's 1935 Winter Convention

The annual A.I.E.E. winter convention will be held in the Engineering Societies Building, 33 West 39th St., New York, N. Y., January 22–25, 1935. The scheme inaugurated last winter of starting the convention on a Tuesday and limiting it to 4 days' duration will be followed again this winter. Tentative plans for the program which are developing rapidly indicate that the first 3 days will be taken up with a number of technical sessions of unusual interest, important committee meetings, and social events, while the fourth day will be devoted exclusively to inspection trips. Details as soon as they become available will be announced in subsequent issues of Electrical Engineering.

A tentative technical program consisting of 12 sessions has been planned to meet the diversified interests of the membership. Some of the sessions are general in scope so as to be of interest to a large number of members while others are more highly technical to meet the needs of specialists. Two symposiums on electronics will treat some of the general developments and applications in this rapidly expanding field of the electrical industry. Another symposium on noise will tell what is being done in the way of measurement and standardization to bring about more quiet operation of electrical equipment. In addition to these 3 symposiums there will be 9 other sessions on subjects as follows: illumination, general overhead line problems, power cables, communication, electric welding, electrical machinery (3 sessions), and education.

Some of the papers for these sessions have already been published, beginning with those for the illumination session which appeared in the August 1934 issue of Electrical Engineering. Other papers have been or will be published in issues subsequent to the August issue on up to and including the January issue. This should make possible a careful advance study of the papers which are to be presented.

General Committee Appointed

The 1935 winter Convention committee is constituted as follows: *Chairman,* C. R. Jones (A'16, M'30), T. F. Barton (A'12, F'30), C. R. Beardsley (A'08, F'30) C. O. Bickelhaupt (M'22, F'28), R. N. Conwell (A'15, F'31), A. F. Dixon (A'14, F'26), H. S. Osborne (A'10, F'21), D. M. Simmons (A'22, F'28), W. R. Smith (M'18, F'30), George Sutherland (A'20, F'27), and R. H. Tapscott (A'18, F'29). The following have been appointed as chairmen of subcommittees: C. S. Purnell (A'29), *dinner-dance;* S. A. Smith, Jr. (A'24, M'31), *inspection trips;* and George Sutherland (A'20, F'27), *smoker.* Other committee chairmen and the complete committees are now being appointed.

General Power Applications Committee Appointed

A complete list of the Institute's officers and committees for 1934–35 was contained in the September 1934 issue of Electrical Engineering, p. 1332–5, with the exception that the members of the technical committee on general power applications were not included, as the committee at that time had not been appointed. Announcement of the membership of this remaining committee was recently made, and is presented below.

The listing of this committee is arranged in the same style as the listing in the September issue, so that all who so desire may make the previous list complete by cutting out and pasting the following one on it.

Power Applications, General

Mark R. Woodward, Chm., Babcock & Wilcox Co., 20 North Wacker Drive, Chicago, Ill.

E. A. Armstrong	H. A. Maxfield
L. M. Dawes	F. J. Meyer
C. W. Drake	John Morse
J. F. Fairman	D. M. Petty
J. F. Gaskill	H. W. Rogers
A. E. Knowlton	L. M. Shadgett

A.I.E.E. Directors Meet at Institute Headquarters

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute headquarters, New York, N. Y., October 19, 1934.

Present: *President*—J. Allen Johnson, Buffalo, N. Y. *Past-Presidents*—J. B. Whitehead, Baltimore, Md.; and H. P. Charlesworth, New York, N. Y. *Vice Presidents*—F. M. Craft, Atlanta, Ga.; A. H. Hull, Toronto Ont.; F. J. Meyer, Oklahoma City, Okla.; G. G. Post, Milwaukee, Wis.; R. W. Sorensen, Pasadena, Calif.; R. H. Tapscott, New York, N. Y.; W. H. Timbie, Cambridge, Mass.; and A. M. Wilson, Cincinnati, Ohio. *Directors*—L. W. Chubb, East Pittsburgh, Pa.; F. M. Farmer, New York, N. Y.; N. E. Funk, Philadelphia, Pa.; H. B. Gear, Chicago, Ill.; P. B. Juhnke, Chicago, Ill.; G. A. Kositzky, Cleveland, Ohio; Everett S. Lee, Schenectady, N. Y.; A. H. Lovell, Ann Arbor, Mich.; A. C. Stevens, Schenectady, N. Y.; and H. R. Woodrow, Brooklyn, N. Y. *National Treasurer*—W. I. Slichter, New York, N. Y. *National Secretary*—H. H. Henline, New York, N. Y.

Action of the executive committee on September 24, 1934, on applications for admission to membership, transfer, and Student enrollment, as follows, was reported and confirmed: One applicant transferred to the grade of Fellow; 4 applicants elected and 16 transferred to the grade of Member; 46 elected to the grade of Associate; 16 Students enrolled.

Reports were presented and approved of meetings of the board of examiners held September 19 and October 17, 1934. Upon recommendation of the board of examiners, the following actions were taken: 2 applicants were transferred to the grade of Member; 13 applicants were elected to the grade of Member and 31 to the grade of Associate as of November 1, 1934; 296 Students were enrolled.

Approval was given to recommendations of the standards committee, as follows: (1) That the "Test Code for Transformers," developed by the committee on electrical machinery and now in revised form, be submitted to the American Standards Association for consideration by the sectional committee on transformers; and (2) that the Institute withdraw from sponsorship of the sectional committee on radio, leaving the committee under the single sponsorship of the Institute of Radio Engineers.

Five members of the board of directors were selected to serve as members of the national nominating committee, as follows: H. P. Charlesworth, Everett S. Lee, A. C. Stevens, J. B. Whitehead, and H. R. Woodrow.

The finance committee reported monthly disbursements amounting to $14,248.97 for September and $20,625.67 for October. Report approved.

A budget for the appropriation year beginning October 1, 1934, submitted by the finance committee, was adopted.

Institute representatives and alternates were appointed as follows: G. L. Knight reappointed to the board of trustees, United Engineering Trustees, Inc., for the 3-year term beginning in January 1935; E. L. Moreland appointed a representative on the standards council of the American Standards Association for the 3-year term beginning January 1, 1935, and H. S. Osborne and E. B. Paxton reappointed alternates for the year 1935.

The Mershon tennis trophy having been permanently won at the 1934 summer convention, the board accepted, with an expression of appreciation, an offer of Past-President Ralph D. Mershon to donate a permanent tennis trophy to remain in the possession of the Institute, the name of the winner of the tennis tournament each year to be engraved thereon.

The Board authorized the coöperation of the Institute with American Engineering Council and other engineering societies in the proposed census of engineers to be taken by the bureau of labor statistics, Department of Labor.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

Membership—

Mr. Institute Member:

The membership committee has set for itself the bogey of obtaining more applications each month than in the corresponding month of the preceding year. Your helpfulness in sending in the names of persons who, you feel, should be invited to join the Institute is making the attainment of this bogey possible. If you have not yet sent in a name to the chairman of your Section membership committee, will you not do so promptly?

Very truly yours,

Everett S. Lee

Chairman National Membership Committee

Future AIEE Meetings

Winter Convention,
New York, N. Y., Jan. 22–25, 1935

South West District Meeting,
Oklahoma City, Okla., Apr. 24–26, 1935

Summer Convention,
Ithaca, N. Y., June 24–28, 1935

Pacific Coast Convention,
Los Angeles vicinity, Fall 1935

Great Lakes District Meeting,
Indianapolis—Lafayette Section territory (Date to be determined)

November 15 Last Date for Suggesting Nominations

The national nominating committee of the A.I.E.E. will meet between November 15 and December 15, 1934, for the purpose of nominating Institute national officers to be voted upon in the spring of 1935. The articles from the constitution and by-laws regarding the procedure of the national nominating committee and the method of submitting suggestions to it were contained in ELECTRICAL ENGINEERING for October 1934, p. 1425; this article also called attention to the fact that members are invited to suggest nominations up to November 15, 1934. For those members who may not have seen the previous article, this invitation is repeated here. To be available for the consideration of the committee all such suggestions must be received by the secretary of the committee at Institute headquarters, New York, N. Y., not later than November 15, 1934.

INDEPENDENT NOMINATIONS

The nominations as made by the national nominating committee are required by the by-laws to be published in the January issue of ELECTRICAL ENGINEERING or otherwise mailed to the Institute's membership during the month of January. Attention of the membership is hereby called to the fact that additional nominations may be made independent of those of the national nominating committee as late as February 15. The following provisions quoted from the constitution and by-laws govern such independent nominations:

Constitution

Sec. 31. Independent nominations may be made by a petition of 25 or more members sent to the national secretary when and as provided in the by-laws; such petitions for the nomination of vice presidents shall be signed only by members within the district concerned.

By-laws

Sec. 23. Petitions proposing the names of candidates as independent nominations for the various offices to be filled at the ensuing election, in accordance with Article VI, section 31 of the constitution must be received by the secretary of the national nominating committee not later than February 15 of each year, to be placed before that committee for the inclusion in the ballot of such candidates as are eligible.

On the ballot prepared by the national nominating

committee in accordance with Article VI of the constitution and sent by the national secretary to all qualified voters during the first week in March of each year, the names of the candidates shall be grouped alphabetically under the name of the office for which each is a candidate.

Suggestions for Research Projects

With the object of stimulating interest in research work, the committee on research of the Institute has collected from electrical engineers in the industry suggestions for research projects suitable for advanced or graduate students and others in the engineering schools who are desirous of undertaking some kind of research work in the electrical engineering field.

A first list of over 100 such research suggestions in 12 branches of electrical engineering has been assembled. A widely varying range of experimental facilities is involved, from the simplest equipment found in any electrical laboratory to highly special facilities which would be available only in a very comprehensively equipped laboratory.

Copies of this list in mimeographed form may be obtained by any member of the teaching staff of an engineering school by merely addressing a request for a copy (or copies) to the committee on research at Institute headquarters, 33 W. 39th Street, New York, N. Y.

"Science Series" Reprints May Be Made Available

The special "science series for engineers" which has been appearing in the pages of ELECTRICAL ENGINEERING during the past year, is now nearing completion. This series consists of a number of articles, each on one of the important fields of present-day science, and each prepared by an authority in the particular field discussed.

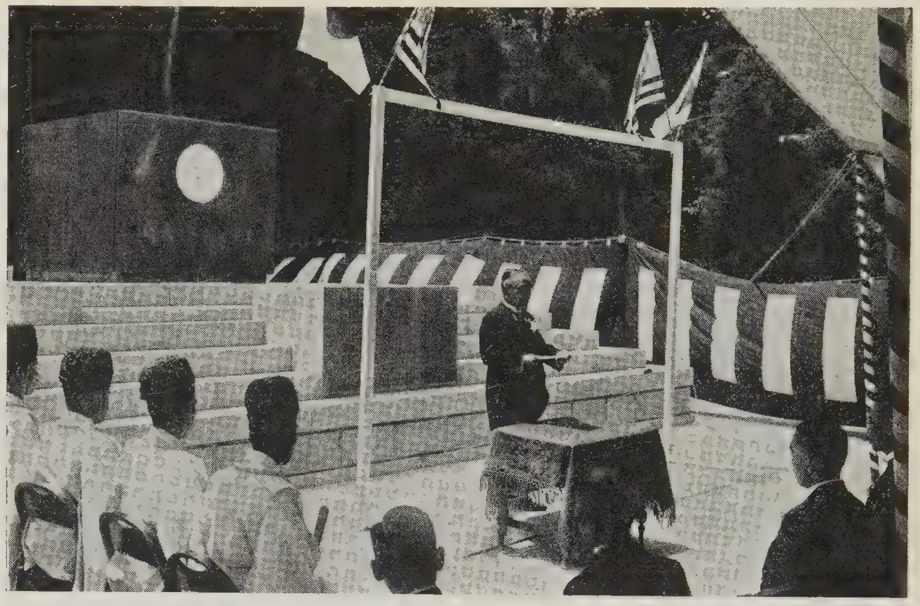
If there is sufficient demand, all the articles in this science series will be combined in a substantially-bound booklet some 80 pages in length, and issued by the Institute.

Such a booklet should be of particular value to the practicing engineer, the recent graduate, the engineering student, and the teacher, as it will afford an authoritative digest of important current developments in the fields of science closely related to electrical engineering.

Anyone interested in obtaining this booklet combining reprints of all the articles in the science series should send an order at once to the A.I.E.E. editorial department. For convenience, an order blank appears in the advertising section of this issue.

M. M. O'Shaughnessy, Hetch Hetchy Builder, Dead. Michael Maurice O'Shaughnessy, dynamic head of the engineering department of the city of San Francisco, Calif., since 1912, died October 12, 1934, in that city, at the age of 70. Although the work that brought him the greatest prominence was the 20-year development of San Francisco's Hetch Hetchy water supply and power project, which he developed from its inception, Mr. O'Shaughnessy directed all San Francisco's municipal engineering work which, in addition to tunnel, street, and sewer developments, included the completion of an extensive municipal railway system. Born in Limerick, Ireland, in 1864, and graduated with honors from the Royal University, Dublin, in 1884, Mr O'Shaughnessy came to the United States in 1885 and spent the next 27 years first in railroad work and then in hydraulic engineering, water supply development, and dam construction in various parts of California and in the Hawaiian Islands. Mr. O'Shaughnessy had been a member of the American Society of Civil Engineers since 1902; in 1920 was president of its San Francisco Section.

Monument to Edison Erected in Japan



IN memory of the late Thomas A. Edison, a beautiful monument was erected in Japan by engineers and followers of the great inventor in that country in the outer-gardens of "Iwashimizu-Hachiman-Gu," one of the famous old shrines located at Yawata near Kyoto City. It was dedicated to the public on May 23, 1934, by Count Keigo Kiyoura, president of the Edison Monument Erection Society, organized jointly by 10 leading scientific societies of Japan.

The site was selected by the executive committee of the Society due to the fact that there Mr. Edison found the most suitable material of bamboo for use in his first experiments with carbon incandescent lamps.

This monument measures 3 m in height, 11 x 11 m at its base, and the stone on the top measures 1.5 x 1.5 x 1.5 m.

There is a tablet placed on the steps in front of the monument, carrying an inscription in Japanese, the translation of which is roughly as follows:

> Thomas Alva Edison, the great American, was a man of unparalleled talent and originality and indefatigable energy. He made many valuable inventions, which gained him a world-wide fame and which contributed much to the progress of science and to the welfare of mankind. Of these, his incandescent lamp is the most notable. However, before its invention, he carried on experiments with various kinds of carbonized fibers in order to find a suitable material for the filament, and found that bamboo was ideal. In 1880, he sent a party to Japan with the object of securing suitable bamboos. Fortunately, through the good offices of Mr. Masanao Makimura, Governor of Kyoto Prefecture, good material was found in the grove of Iwashimizu-Hachiman-Gu. With this material, Edison was at last able to gain practical results. Who can deny the grace of the Hachiman gods in his undertaking? There are no cities in the world where electric lamps are not lighted, nay, even out-of-the-way hamlets enjoy this great boon of civilization. Thus, his services have certainly been stupendous! Edison said that invention was the result of ninety-nine per cent of perspiration and one per cent of inspiration. Indeed he was a self-made man and a man of strenuous effort, and this great invention was the outcome of his painstaking labor. Wonderful services can be rendered only by such an extraordinary man as Edison. His name abundantly deserves to be handed down to posterity. Consequently, with the support of those interested, we have erected a monument in memory of Thomas Alva Edison at Otokoyama, historically related to his success, for the purpose of immortalizing his brilliant exploit and proclaiming to the world the divine virtues of Hachiman Daijin.

The photograph reproduced in the accompanying illustration was taken at the unveiling ceremony and shows Dr. Eiji Aoyagi, professor of electrical engineering, Kyoto Imperial University, who served as chief of the executive committee, delivering his address. At the left are 4 priests of the Iwashimizu Hachiman Shrine.

On the white disk in the face of the rectangular stone at the top of the steps is carved a bas-relief of the profile of Edison, not clearly visible in the photograph reproduced herewith. The inscription quoted above is carved in the face of the lighter stone located part way down the steps.

What Place the Engineer in the Changing Economic Scene?

RECOGNIZING the obligation of the engineer to make his especial contribution to the complex problems of human relationships, social and economic, the Institute's New York Section scheduled 2 prominent speakers to appear before a general meeting of the Section in the Engineering Societies Building, New York, October 10, 1934.

Speaking under the title of "Is the Economic Scene Changing?" Dr. Virgil Jordan, president, National Industrial Conference Board, presented some of the fundamental considerations of the present economic state, the conditions which produced it, the manner in which its significance may be interpreted, and pointed out the relation of the engineer to modern trends; Col. W. T. Chevalier, vice president, McGraw-Hill Publishing Company, directed the attention of the engineer to other aspects of the situation, and indicated the lines along which opportunities lie ahead for the engineering profession.

Doctor Jordan has been active in the field of economics since his graduation from college in 1912. Between 1920 and 1929 he was chief economist and editor of the publications of the National Industrial Conference Board. Between 1929 and 1932 he was economist for the McGraw-Hill publications, and in the latter year returned to the National Industrial Conference Board as its president. In 1928 he was the organizer and chairman of the Conference of Statisticians in Industry, and in 1931 was the conductor of an investigation of American consumer expenditures.

Colonel Chevalier, following many years' experience in the construction field, became a consultant on technical advertising and promotion in 1921, and in the following year became associate editor of *Engineering News-Record*. He became business manager of this publication in 1923, and since 1927 has been publishing director of civil engineering and construction publications of the McGraw-Hill Publishing Company. During the period 1917–19, he was successively captain, major, and lieutenant colonel of engineers with 11th U.S. Engineers on field service in France, mainly on field fortification, road and railway construction and maintenance; he is at present colonel, Engineers Reserve Corps.

In view of the significance of social and economic trends, and their influence on the future conditions under which the engineer may be called upon to work, abstracts of these 2 addresses are presented herewith.

Dr. Jordan's Address

To understand accurately the position and prospects of the engineer today I think that it is first necessary not only to secure a firm grasp of the economic actualities of the present situation, which in itself is difficult and rare enough, but also to explore some aspects of the social and political psychology of the situation which may be unfamiliar.

The situation today is the result of exceptionally powerful psychological and perhaps biological forces that are at work acting upon the economic realities which underlie the whole picture. And both these psychological and biological forces, and the economic realities themselves, are largely obscured today and remain unseen to most of us.

The economic scene which we are now considering is in my view unchanged fundamentally. It has always been unchanged in its essential elements. What is changing is primarily men's conception of the economic scene and their attitude toward it. And it is this change in conception and attitude which is the source and origin of the problem that confronts us all and confronts you especially as engineers.

We are living in an age of what I call economic illusion, or you might call it social self-deception, or political hypnotism. The engineer has, partly unconsciously and partly deliberately, been the cause, or an important factor, in the development of that economic illusion. He has now become one of the foremost victims of it. And finally, if we are all to be saved from the disaster to which any such widespread social illusion leads, the burden of salvation will rest largely upon the engineer.

Now the essence of this economic illusion which is the center of my discussion, is the idea of automatic, universal, effortless, and unlimited abundance of passive prosperity and permanent security, provided by a self-operating industry under the compulsion of an all-powerful and all-wise state, a state which has become the new god, the basis of a modern religion, the great protecting and flourishing mother, the great beneficiary of everyone, which creates all things and makes all things perfect and permanent and secure. This is the essential idea in all of its manifestations that permeates the political and social atmosphere today, not in this country alone but in most of the western nations. In its deepest sense this illusion, or this conception, may be called a psychosis of that great human mass, great mass of humanity that was thrown suddenly into existence during the short span of the past 150 years when the population of the Western world trebled as a result of the sudden development of the power age.

Perhaps this single statistical fact is the germ or key to the whole situation. From 1800 up to the present time, in that 130 years, the population of Europe increased from 180,000,000 to 540,000,000, becoming 3 times as great. Now that sudden hurling of this great mass of humanity in the short space of 130 years, into existence, in a biological sense at least is the basis of this tremendous psychosis that has swept and has come to its crucial development in the present time in all of the Western countries. The mob or the masses—what I like to call that terrible abortion—of the industrial revolution, born of the sudden mating of science and nature, abruptly projected into a world which it did not create, which it took no part in creating, and which it does not understand, that mass, that mob is unconsciously searching today for escape from its responsibilities and the struggle of existence imposed by its relentless realities of life, trying in many ways to return to the womb of passive effortless gestation from which it sprang.

Mass Indolence Is a New Phenomenon

Individuals of course have always, for the most part, been essentially lazy. Perhaps a basic, the most primitive economic principle of all, is that of trying to get the greatest possible satisfaction with the least effort. Only relatively few individuals in any period of history have been in a real sense centers of creative energy. But the phenomenon of organized mass indolence or mass laziness, is a new phenomenon in human history, organized in the sense that it is not only physically organized, but that it has developed a whole philosophy, a whole structure of theory as a rationalization of its indolence. It is the first time that indolence has been erected into an economic and political principle upon which a system of social organization is sought to be based.

Now all of us in some measure today, whether we are conscious of it or not, are subject to this acute psychosis that the industrial revolution has slowly developed in all of the Western world. We live willingly or unwillingly, consciously or unconsciously, in a sort of dream state of wish fantasy, fearing effort and risk, troubled by nightmares and paranoias of persecution and oppression by wicked and powerful individuals and groups, suspecting, envying, even hating, and seeking to destroy the distinctive creative individual or institution, fleeing the strenuous life of personal effort and enterprise, preferring the secure life to the strenuous life; searching incessantly for security, unwilling to awake from a dream world and grapple with realities, surrendering easily to the embrace of the vision of passive plenty and permanent protection.

That is perhaps a fundamental description of the basic state of mind of most people in the Western nations today, a brief summary of their psychological trend. I say it affects all groups, and I want to be perfectly explicit in that respect by making it clear that I recognize above all that it affects the business group particularly. It is not merely a phenomenon of the employee group, but has become today a characteristic trend of mind of the employer or enterpriser group in this country particularly. Business men's whole behavior today is conditioned by this search for security and this expectation of passive, profitable operation. You see that reflected of course in the tenacity with which business men cling to the idea of protecting profits by various devices of price fixing; you see its most magnificent embodiment in all of the beautiful dreams of N.R.A., but you see it also even in the scientific group, and to a large extent among the engineering group, in the decline of pure research activities, in the general assumption that it is desirable to restrict inventive advance, in the general acceptance of the conception of the men as of the machine which pervades the minds not only of business men but to an increasing extent of a great many men in the scientific field as well.

This Illusion Causes a Regressive Trend

Now this whole trend toward the establishment of a passive consumption and static security system, which we see manifested everywhere today, is fundamentally a regressive trend. It is regressive biologically and also in the economic and political senses, a relapse or a return to an earlier form of life, of a less highly developed and highly creative form of life. Biologically the symptoms of it are obvious enough to the eye. It reflects itself of course in the great phenomenon of declining birth rate in all of the Western nations, in the fear of children, the fear of the new generation, and the fear of death; the relatively diminishing proportion of young people in the population and the increasing proportion of older people. These are the first symptoms of the disappearance of race vitality and of biological degeneration.

Along with that of course comes the disappearance of personal individuality, or rather the tendency to regard manifestations of individual action as anti-social, as dangerous, disruptive, and in consequence the increasing emphasis upon the importance and necessity of organized regimentation and standardization—all of them reflecting the trend toward a termite organization of life, socially and politically, which we have manifested in more or less perfect form or a highly advanced form in Russia, Italy, and Germany today.

This Age of Plenty

Now I want to emphasize particularly the economic expressions, manifestations, and implications of this age of economic illusion. The first, of course, is the widespread acceptance of the idea of the automatic productivity of industry, the feeling that modern machine industry has become in a very real sense of dehumanized process in which the human factor is no longer an important element; that it has reached the stage of an automatic affair, so that the rôle of management in modern industry is constantly minimized day by day, and even to the point of being ignored altogether in many manifestations of governmental policy toward industry.

We all believe in one way or another that we are living today in an age of plenty, in a surplus economy, which has occurred by some species of magic which we don't fully understand but which we associate with the activities of the engineer and the scientist, and that that age of plenty or this surplus economy has an inherent tendency toward excessive production, toward over investment in productive facilities, toward the creation of excess productive capacity; and that our problem is essentially one of control of this abundance, this avalanche of abundance that threatens us all. As a direct consequence of that general idea which is universally accepted so far as I can see, we have put all our emphasis in our thinking today upon problems of consumption. We believe without question that our economic and political difficulties are all manifestations of under-consumption, of the inability to consume, and that our essential task politically, socially, is to devise means for increasing consumption through the redistribution of purchasing power or income in money terms.

The "New Deal"

Now all of those ideas are directly embodied in the whole New Deal program as we call it, that is, in all of the legislative and administrative policies of the present administration, with the concepts that we increase our prosperity by increasing the amount of money in circulation, increasing the prices of commodities; that we increase prosperity by stimulating spending, and buying and consumption of products; that we must do that by a vast program of public expenditure in the form particularly of expenditure and credit creation for non-productive works, non-productive public facilities; and that we can increase our prosperity by bringing about certain very marked forms of redistribution of money purchasing power, such as extracting it from people who live in cities and paying it to people who live on farms, by increasing wages, money wages, by shortening working hours, by developing plans for old-age payments, payments to the aged who are increasing constantly in proportion to the population, and whose function is purely a passive one of consumption.

Doctor Jordan

Along with those ideas goes of course the general acceptance of the idea of restricting profits in order to divert purchasing power from those groups in the population who can't immediately or directly spend all of their income, but must invest it in various ways, thereby building up excessive productive capacity and preventing adequate consumption of goods produced. Those ideas also carry the policy of high taxation of higher income brackets and of corporate surpluses for the same purpose, diverting purchasing power immediately and directly into consumer channels. They carry also the implication which is directly embodied in many of the codes, of restrictive production and of control of investments, expressed in the Security Market Act and the Stock Exchange Regulation Act. They carry the idea of price fixing as price fixing under governmental control in order that the government or governmental agency may properly apportion the flow of consumer purchasing power as between wages and payments upon capital investments. They carry the implication also of the guarantee of profits, and finally there blossoms in the idea which is now very seriously considered, of adapting the European conception of cartels to the organization of American industry.

So that by thorough-going group organization under governmental control there may be complete regulation of the flow of purchasing power by industry as between wage earners, employees, or as they are commonly thought of, mere consumers, and recipients of payments upon capital investments.

Result—A Lowered Standard of Living

Now all of this process, all of this legislative structure which embodies these general philosophies, the philosophy of passive consumption which is the basis of the economic illusion under which we live, inevitably must lead to a lower standard of living. The standard of living, of course, is a simple and direct function of effective production, in which the essential factors, apart from natural resources, are human effort, intelligence, organization, technical knowledge, saving, and risk taking. Today all of these factors are supplanted by the general process of political prestidigitation and governmental magic, monetary magic, fiscal magic, and regulatory sleight of hand—all of them designed, through the redistribution or the redirection of the flow of purchasing power to raise the general level of prosperity. This is called planning today, a word that covers the confusion and vagueness and fogginess of thought that underlies the whole process; and it consists mainly or practically altogether in devices for redistribution of income. That is what it comes down to essentially, not to increased production, which is the basis of the standard of living, but to appropriate, redistribute, and stimulate consumption of foods and goods produced.

Reduced Production Prolongs the Depression

As I said it is universally assumed that the problem of production today has been completely solved, that the standard of living as a function of productive, effective production, is infinitive, but that the problem of distribution and consumption is unsolved, that it remains for effective governmental action to solve, and that it must be solved by the state alone through deliberate action.

Now of course from my point of view our essential problem is that of effective production. The fact that we do not produce and cannot produce effectively is the reason we have had a depression and is the reason we are not recovering from this depression. Production is hampered in this and every other country by an enormous structure, an elaborate network of artificial restrictions and false concepts, popular concepts as well as political and governmental concepts. In this country we are suffering today from what may be said is a universal sabotage of production by labor and also

by management and by the agencies and institutions that control the flow of capital for industry, a sabotage that reflects itself in widespread inefficiency of labor in many forms in almost every industry, a deliberate, conscious, direct withholding of productive effort in almost every field of labor today by a fear of capital investment and a complete unwillingness of risk taking in every field.

Those factors that tend to sabotage and hold back effective productive effort in every field are the basic reasons why we are as we are, why our standard of living is what it is, why it is so difficult, so slow to raise it.

Trend to State Capitalism

Now that situation and that psychological background are moving us steadily and rapidly in this country toward the establishment of a comprehensive system of state capitalism under central, bureaucratic dictatorship. That is the natural, inevitable response in political terms to a psychological and economic situation such as confronts us here and now. This network, this structure of governmental control, of artificial restrictions placed piecemeal, developing spontaneously in response to these psychological conditions in every field of industry, invite constantly an extension of such controls. They carry with them the inevitable process of expanding regulation, because such regulation exercised in one element or with respect to one part of the economic picture, creates unbalanced conditions and disturbances in the economic balance which necessitate further injection of state power, of governmental control in other parts of the picture. There is no escape from that.

State planning or state regulation cripples inevitably the natural forces of productive effort and moves relentlessly toward socialism. There is no break in that process; there has been no break in that process in any Western country. It has moved steadily from the first rudimentary and elementary injection of state power or state interference in the natural processes of production, to complete socialization and complete dictatorship in the end. That of course carries with it inevitably the implication of the end of personal liberty and individual action in every field, and implies a radical and complete change in our whole political institutions; because both in its origins and in its development, private capitalistic enterprise as distinguished from governmentalistic enterprise is the same thing as free democratic or republican institutions. They originated together and they have grown up together, and they will come to an end together. One cannot survive the other. In all of the Western nations that progressive parallel destruction of democratic and republican institutions and the destruction of private, capitalistic enterprise, have proceeded very far. Even in Great Britain which stands out in the world today as perhaps the most, the noblest old figure among the nations as the embodiment of the principles of private capitalistic enterprise and democratic institutions, beneath the surface has undergone a transformation and is separated only by very short steps from the more advanced stages of capitalism which we see in Germany and Italy and Russia, and to a large extent in the United States. Today in the United States between 40 and 50 per cent of the total national income in monetary terms passes through the hands of governmental agencies and is taken out of the channel of free disposition by private enterprise.

Engineer Has Both Aided and Been the Victim of This Illusion

Now the engineer, to come back to the subject with which we are concerned, has aided this process in many ways. He has aided it by his scientific, technical achievements, and by his labor-saving devices as they are called, which have created or provided the basis for this widespread illusion of automatic productive power. He has provided the basis for this universal idea that labor, effort, and risk taking are becoming more and more superfluous in our economic system. Scientists and engineers themselves, aside from the general effect of their technical contributions, have helped to foster this illusion of abundance by constant paper demonstrations of the enormous productive capacity of modern industry under certain theoretical organization of its forces of production. These paper demonstrations always ignore the human obstacles and the human inertia which underlies the whole organization of production, which is the fundamental reason for our inability to utilize our productive forces to the full extent theoretically possible, and these paper demonstrations ignore also that basic law of diminishing returns, and the more basic law perhaps of the degradation or dissipation of capital, which is in economics quite comparable to the principle of entropy in physics.

Now while the engineer has in all of these ways undoubtedly been a most important factor in stimulating and developing this era of economic illusion in which we live, the tragic fact is that they themselves have become the most pathetic victims of this illusion, because it has found its expression in public policies and in social principles which inherently regard the engineer and his kind as enemies of progress and prosperity. The engineers are regarded with aversion in the public mind as agents who are constantly contributing, unwillingly, perhaps, just by force of nature, of their temperament and their training, to this unbalance of production and consumption which is the heart of our economic problem.

Responsibility of the Engineer

Now where does it leave us; where does it leave the engineer from the point of view of the future, this whole picture that I have been describing in such a sketchy way, because I couldn't hope to cover the whole field of problems involved? It seems to me quite clear that in the end the solution of the problem, or at least the task of release from the dilemma in which we find ourselves, comes back in the last analysis to the engineer. In the end only he can offset or compensate for this vast destruction of productivity which the intervention of the politician and of the planner and of the mob must inevitably lead to. That is what is taking place today under our eyes, a tremendous destruction of productive power the world over, progressive because nothing accumulates so rapidly on a geometric scale as paralysis of productive power in thickly populated and highly organized society. The task of providing and maintaining even the degree of abundance and security which has existed up to 1929, a very formidable task as I view it looking ahead, the task of maintaining that degree of abundance and security will rest primarily upon the engineer.

In an age of economic illusion such as we live in, the engineer is more indispensable than ever if he himself is unflinchingly alive to the realities of the economic problem that confronts us. Among the figures that move in this economic scene, only he can save this great mass of humanity from self-destruction. And he must not expect to be thanked for it. That mob that rules destiny today in all of the Western world will take his service for granted, it will not show any gratitude for it because they have no understanding of its essential significance at all. But while he is performing that task, he should not neglect his responsibility as, let me call it a propagandist, in inculcating the discipline or gospel of realistic thought about these problems. The rarest thing in the world today is that unflinching realistic approach to these basic economic and social problems, because if he acts effectively as such a propagandist he may, I hope, in time spread a little of that realism into the political sphere. The burden of creative accomplishment as you know full well, and as all of those who have studied the course of history with a realistic eye know, that burden of creative accomplishment always rests on a very few in every society, a few who must carry the rest on their backs, usually without appreciation, without understanding, and now, in the face of outright antagonism.

Other groups in the community, if there are any who can be brought to understand that situation, must aid those creative few who are carrying the mass, and they must be mobilized and I think that they are to a certain extent being mobilized today in the United States to aid in protecting these creative forces from destruction.

Support of the Present Administration

It seems to me, coming down to the situation which confronts us these very days through which we are living in this country, that from the point of view that I have been describing to you, the President of the United States needs, to the fullest extent, the sympathy and support of every American who has any deep understanding of the dangers that confront us in this country, whether we approve or not of the things that have been done during the past year and a half. The essential danger that faces us now at the end of 1934, and that will face us more critically before 3 or 4 or 6 months have elapsed, in my opinion, is that the President may become the helpless victim of forces which he has set in motion or which have been set in motion in this country during the past year and a half, and instead of being able to serve effectively as a leader of those forces as he has up to the present, there is a real danger in the next few months that he may become their helpless victim and be swept away by them.

And to avoid that, whatever one's political sympathies or general philosophy may be, as Americans we have to realize that the crisis to which this era of economic illusion strongly stimulated by governmental policies has brought us, may lead to chaos and complete destruction of our whole economic and political system in this country.

So that in that situation the engineering mind which has not been brought to play effectively in a political sense up to the present, may be called upon I believe to play an important part, both directly in its contribution to the solution of some of the practical and immediate problems that confront us, and as a protagonist or propagandist or as a vehicle of expression to the public mind of some of the more realistic points of view toward these problems that we urgently need to grasp today if we are to avoid some of the dangers that lie ahead.

Colonel Chevalier's Address

In order that we may be clear to start with, I want to say what you are going to find out very quickly, that I am not an economist and have no economic pretensions. I am going to try to make a picture for you of this scene that Dr. Jordan has presented to you as a philosopher and an economist, as it looks to the eye of an engineer. To indicate the solution of all of these problems, even, from the standpoint of the engineer only, is a task far beyond my poor powers, but perhaps if we can reconcile some of these views as each of us sees them from his own eyes, it may be a fruitful visit.

Dr. Jordan has well emphasized the fact that it is fundamental in the engineer's philosophy that production is the fundamental factor in our civilization and in our material progress. And if the engineer were to define his function in a phrase he would have to say that his major purpose is to increase the productivity of his fellow men so far as the physical world and physical agencies are concerned. Therefore, if some of these philosophies of restriction upon production should prevail, the engineer is in a bad state indeed, for he has lost the reason for his existence. Now I should like to take, as a text perhaps, a clipping from an issue of the *New Yorker*. It appeared about the time of the airmail controversy. And writing under the head of a "Reporter at Large," Morris Markey had this to say:

"I don't know much about the disputes down in Washington. I have gathered vaguely that a gentleman named McCracken had to get arrested and that a lot of papers were destroyed which shouldn't have been. All of that seems pretty remote when you are standing out there on the field watching a man like Thaddok pull one off the ground and strike off for the mountains to Chicago. I don't think Thaddok or Texas or this fellow Mike knew anything about manipulation of contracts or that he cared anything about such affairs. (Now this is the significant part.) It made me feel a little sore to think that they and all those roster of mechanics and hangar men and such, all the engineers who burnt their eyes out over drawing boards to make better airplanes, and all the men who have watched hundred hour full throttle tests on new engines, to think that such a decent and competent crowd should take it on the chin now and be discredited by inference at least because a little crowd of slickers 2 or 3 years ago made monkeys out of a little crowd of politicians. But this is no doubt a bootless sort of complaint. Honest and deft hired men have suffered before, I seem to recall, because of the sad fact that their bosses smelled money and lost their honor in the race for it."

Making the System Safe for the Producer

Now I know how easy it is to over-simplify a problem and therefore I run the risk of over-simplification when I say that from the standpoint of one engineer at least the only problem that confronts us in this whole economic muddle is that of making the system safe for the producer.

Colonel Chevalier

Now I recognize 3 kinds of producers. There are the men that work with their hands, and the men that work with their heads, taking into account the scientist, the engineer, and the manager; and the men that work with their thrift, those that deny themselves the current satisfaction of the wealth they have created in order to make possible the creation of those agencies that are going to multiply our productive capacity in the future, that provides the tools with which the engineer has to work.

Now with all this productivity that has been created through the improvement in our technology, our producing plan, and in our management, I have the feeling, which I cannot prove, that it would be relatively easy to create an abundance for all of us if we could confine it to the producers, the 3 classes that I have mentioned. The reason that we are not able to confine it to the producers is because somewhere in the circuit we manage to cut in on the distribution of the wealth we create a vast horde of parasites who by speculative manipulation and the operation of credit and financial agencies, are enabled to reap a profit on a vast scale where they did not sow. And everyone who by such manipulation puts himself in a position to command wealth without creating it, is taking it away from someone who has created it.

Now you say, well, but speculation is the life of progress. Yes, creative speculation is the life of progress. But predatory speculation is its death. It to me is the greatest enemy of the engineer in the economic order, and regardless of what I may think about some of the funny things that have been done in Washington during the last year, I am thoroughly in sympathy with everything that can be done to curb excessive predatory speculation whether it be done through a securities act or control of the exchanges, or by some closer supervision of the use of credit.

Now we talk a great deal about the prosperity of a few years ago. Dr. Jordan has talked to you tonight about all of the troubles that we have and may have if we don't watch out. In my opinion these troubles were born from 1923 to 1929, and not in the last year or the last 2 or 3 years. We heard a lot about the prosperity of a few years ago. Well, who had the prosperity? I recently found for example that if you compared 1923 to 1929, the nonfinancial corporations during that period showed an increase in profits of only 14.1 per cent. Those were the productive activities of the country, and that was their increase in reward. During the same period from 1923 to 1929, the financial corporations showed an increase in profits of 177.3 per cent.

Prices and Production Can't Be Fixed

Now I am not worried about the future of the engineer. I don't think a lot of these things that Dr. Jordan has told us about are going to happen. I hope they don't. Every engineer that I know has had to scratch his head harder than ever, first of all to get a job, and secondly, to make good on it when he had it. Every manufacturer that I know has had to devote more energy and more technical skill in order to survive than he had to exercise 10 years ago to make a profit.

Now I agree with the foolishness of a lot of things that some of our industrialists in their despair of a year ago have tried to do. I sat down in Washington last fall and worked with a great many of them trying to resolve some of their difficulties and to get them through the N.R.A., and worked with them sympathetically. And the 2 things that everyone wanted were the chance to fix the prices and the chance to stop anyone else from going in business. Well now, that looks good from a close-up, but when you get away and look at it from a distance the whole thing loses scale somehow, it is out of proportion. I don't know anything about some of the higher aspects of economic philosophy, but I do know this, that if we are going to keep this so-called capitalistic system the 2 things we can't do are fix prices and stop the entrance of new capital into production. The industrialists today who try to do those 2 things are doing more to upset the capitalistic system than all of the soap box orators from here to the Nevsky Prospekt in my opinion, because a principal prop of the capitalistic system is a free competition to enable you constantly to reduce the cost of production so that more people can be brought into

the market. Only in that way can we justify the withdrawal of wealth from current consumption in order to provide the new productive capacity. And furthermore, if we freeze the methods and process by keeping new enterprise out of a field, we are doing the surest thing possible to stop this increase in our productivity that is the life of the system and constantly gives employment to the capital that distinguishes it.

Heritage of the Capitalistic System

So many people have said, "You see we have gone along for 150 years here and we have done awfully well. You know the best thing to do is to let it ride; don't disturb anything. We have got along fine and we have prospered in comparison with the rest of the world. Look at what we have done in 150 years in this country under this system we are operating under."

Well, all right, as an engineer I look at it and what do I see? I see 150 years ago when we took over the establishment, a set-up. Here was 3,000 miles by 1,000 miles of the earth's surface filled up with natural wealth beyond the wildest dreams of a Coresus, and a little handful of white people on the Eastern shore with just a few red savages to be driven off the reservation, and it belonged to that little group of white people. They inherited the earth and everything above it and underneath it. And for 150 years we have been living on our capital. We have been living on our patrimony, and we have been able to make the old speculative thing work because every time we cleaned out one bunch of suckers there was a new place for them to go and dig up some more for the wise ones to take away from them on the next turnover.

Now that is not funny; that is a fact. That is what we have been doing for 150 years in this country. Now the engineer has been both the beneficiary and the victim of that process because that psychology of easy money through speculation was present.

When I say that we have got to make the system safe for the producer, I mean that we have got to make finance work to serve creative industry rather than simply to serve finance and speculation. That is the salvation of the capitalistic system in which I believe, and in spite of all its faults I love it still. The capitalistic system has a lot of friends, but I remember the definition of a friend. A friend is a man that knows all your faults and still likes you. Well, I am a friend of the capitalistic system in that respect and I want to see it survive, and it is not going to be made to survive by just damning the government and everything that it does to deal with an emergency.

Thr Job of the Economist

Now Dr. Jordan says that it is the engineer's job to help the community to get out of the mess that the community says the engineer put them in. I don't agree with him. I say that that is the economist's job. The trouble is that they can't get in a huddle long enough to agree on anything. When I say it is up to the economist I mean this, that if we have developed a great productivity, and no one doubts that, and if the people would like to live on a little higher standard than they have, and get the benefit of some of this productivity, you call it redistribution of income or anything you please, I don't care; I say we should be able to reconcile those 2 conditions and not have one crowd over here starve because they can't get rid of their surplus and the other crowd starve because they can't get it.

My theory is that that business of effecting that change of wealth is a function of our financial system. If that isn't what a financial system does, then it is a mess, because it doesn't do anything else; it doesn't produce any wealth. Look at these corporations that got the 177 per cent increase in profits in 7 years, just what wealth did they add to this world of ours? They rendered a service, yes, the same as a cash register, the same as a bookkeeper. I am not belittling that service. But when somehow or other there is such a proportion of the wealth we create that trickles out in that process somewhere and sticks and doesn't get from producer to producer, then I think there is something wrong. And I say to solve that problem is the job of the economist.

The Job of the Engineer

Well, what is the engineer going to do about it? Well, the first thing I think he ought to do is keep everlastingly prodding the economist. Now you go down the street and get these fellows that know all about money and finance and banking and credit, and you get together with them and come back and show me how we are going to effect this change of value and services that is going to make use of the enormous productivity that has come about during the last hundred years.

That is the first thing we can do. The second thing we can do, that we are going to have to do, is to continue building. I am now getting away from the personal problem into the problem of the profession. We are going to have a job to do in the next decade to make up for what we have lost in the last 2 or 3 years. There is a perfectly enormous arrearage of productive effort that we have got to put to work.

Now if you think the job is finished in this country, ride across the continent on a train and see a lot of these overgrown mining camps that we call cities and towns today. I am not reproaching them. What they have done in the last 50 years, some of them, has been remarkable, but it isn't a circumstance to what they are going to do in another 50 or 100 years, what needs to be done to make them real cities, typical of American civilization.

Now I don't know my facts, but when Doctor Jordan was talking about the fact that pure science had gone on a holiday or something of the sort, I couldn't challenge that statement, but I didn't think so. I thought we had built up quite a lot of scientific research in the last few years that has yet to be applied to practical purposes, due to the breakdown of the machinery that I am talking about.

Now, then, we have not only got to rebuild a whole lot, but we are going to have to replace a lot of old tools that have become obsolescent. So the engineer is going to have a big job there in my opinion. Then we are going to have to develop refinement of technique and method to a degree we never dreamed of before. I remember in my own short lifetime when I first started in the construction industry that construction equipment was about on a par with agricultural machinery, crude, rough castings, just stick a shaft through a casting and you had a bearing. Today we build construction machinery like automobiles, roller bearings, special steels, forced lubrication—one power shovel costs 12 or 15 thousand dollars. So we have developed constantly as we have been drawing down that supply of our natural resources. And as we have gone through that process we have been compelled to make better and better and better use of them. And that has led to refinement in engineering practice and in my opinion we are going to have to do more of that in the future than we have done in the last 30 or 40 or 50 years, because we are going to have to make what we have got go farther.

Developing the Social Consciousness

And finally we are going to have to develop this consciousness that Dr. Jordan was talking about, that we are something more than hired men. The greatest thing that is wrong with the engineering profession is our psychology.

In order to broaden our interests, one of the first things is getting a better grasp of the purpose of what we are doing, the economic and social objectives of our work. In Richard Harding Davis' famous yarn "Soldiers of Fortune," I remember one place when Clay was working on the mines and Alice Langham's father was his em-employer, and he said to her, "Miss Langham, all you see is a lot of rock to be blasted out and carried down here and dumped in a ship to be carried away and help make your father rich; that is all you see in my job. But I see a mountain of ore there, and in that ore there are facilities and services and utilities innumerable that I am going to take out and send to men who will fashion them into instruments to help men live better, go farther with their lives." And he used the expression that I always have remembered. He said, "I prefer to bind a laurel to my plow than to go through life calling myself hard names because I am a plowman."

Now we have got to bind a laurel to our plow. I don't mean that that is going to make us richer in the pay envelope at the end of the month, although it may. If more of us will have that vision of our work, and more of us will translate the productivity of the modern science into service and commodities and goods for the producers of wealth instead of into speculative profits for the few who by hook or crook put themselves in a position to control it and manipulate it; then we will be doing a good job for the profession and we will probably profit ourselves in the process.

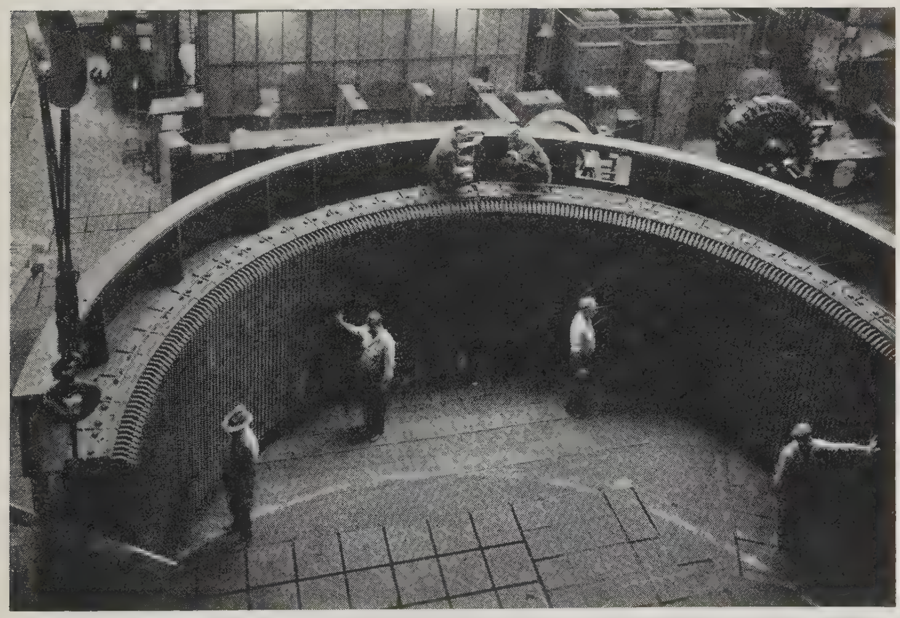
Interests of Business Men

Now in closing, just to get the record straight, I don't want anything that I have said here to create the impression in your mind that I am ranting against the people

who save their money and provide capital and make honest investment in the productive agencies of our economy—not at all. They are the very people whose interests I would like to see better protected. I am not at all finding fault with the business men. You know one of the most pathetic things in the world today is the average industrialist, the producer, the man whose energy has built a plant, whose driving power has brought together an organization and inspired it, and gone out and sold a product, who has made a real contribution to our economy and employment of capital and labor and in service to his community, those real industrialists of which we have so many in this country—somehow or another they allow the forces of finance and speculation to convince them that their interests are in common and every time someone attacks the citadel of waste and depression, or rather depredation and speculation and manipulation, it is very easy to rally a bunch of these good old sturdy producers to come and do their stuff in order to prevent the harness being put on, or a yoke or something of the sort, because they think their interests are the same; they are not the same. Some day they will see that their interests as producers are diametrically opposite to the interests of those who seek to acquire without creation. And we will never have a Utopia, but all that I hope is that out of the next generation we may learn to put a premium on creation of wealth rather than acquisition of wealth, because that is the essence of all that I have been trying to say to you tonight of an engineer's vision of what we are going through and what we hope will come out of it.

A.S.M.E. Elects Officers. Officers of The American Society of Mechanical Engineers to serve for the year 1935 were recently elected. The newly elected president of the A.S.M.E. is Ralph E. Flanders, president, Jones and Lamson Machine Company, member of the Industrial Advisory Board of the N.R.A., and of the Business Advisory and Planning Council. He is a national authority on machine design and construction, representing the A.S.M.E. on the sectional committee on standardization and unification of screw threads since 1921, and serving as chairman since 1930. He was president of the National Machine Tool Builders Association in 1924, is a director of the Social Science Research Council, and is a lecturer at the Tuck School of Business Administration at Dartmouth College. He is known to members of the A.I.E.E as chairman of American Engineering Council's committee on the relation of consumption, production, and distribution; progress reports of this committee were published in Electrical Engineering during 1932 and 1933. Newly elected vice presidents of A.S.M.E. are James H. Herron, president, James H. Herron Company, Cleveland, Ohio; Eugene W. O'Brien editor, *Southern Power Journal*, Atlanta, Ga.; and Harry R. Westcott, president Westcott and Mapes, Inc., New Haven, Conn. Newly elected managers are B. M. Brigman (M'28) dean, Speed Scientific School, University of Louisville, Ky.; J. W. Haney, professor of mechanical engineering, University of Nebraska; and Alfred Iddles, vice president, United Engineers and Constructors, Inc., Philadelphia, Pa.

Assembling the First of the Boulder Dam Generators



THE first of the 4 Boulder Dam generators each rated at 82,500 kva, is shown here in the Schenectady, N. Y., works of the General Electric Company. Another of these generators is under construction in the same works, and the 2 others are being built at the East Pittsburgh, Pa., works of the Westinghouse Electric and Manufacturing Company. The sections of the stator frames are shown here being bolted together. Before delivery at Boulder Dam scheduled for November of this year the stator will be taken apart for shipment by rail, 40 freight cars being required to transport it. Brief information on these generators has been given in Electrical Engineering for November 1933, p. 796–7, and for March 1934, p. 499.

Naval Architects and Marine Engineers to Meet. The Society of Naval Architects and Marine Engineers will hold its 42d annual meeting in the Engineering Societies Building, 29 West 39th Street, New York, N. Y., Thursday and Friday, November 15 and 16, 1934. A technical session is scheduled for each morning and each afternoon of the 2-day meeting; 3 papers per session. At the Friday morning session David Arnott, chief surveyor for the American Bureau of Shipping, New York, will present a comprehensive paper on "Some Examples of Arc Welded Ship Construction."

Exposition of Power and Mechanical Engineering. The 11th National Exposition of Power and Mechanical Engineering will take place at Grand Central Palace, New York, N. Y., during the week of Dec. 3–8, 1934. This exposition, which is held every second year, is being held concurrently with the annual meeting of The American Society of Mechanical Engineers. Exhibits now under construction are coordinated to emphasize the saving of power costs. This keynote reflects the need of modernization and replacement of old and obsolete equipment. The exposition is said to offer a setting in which the evaluation of materials and machines to be used for rehabilitation and new construction is aided by the possibility of comparing a wide range of competitive items at the same place and time.

Former Chairman of Pittsfield Section Dies. William Porter White, manager of the customer division of the central station department of the General Electric Company, died Sept. 22, 1934. He was born at Beaufort, S. C., Sept. 18, 1885. Following his graduation from Clemson College in 1906 he entered the testing department of the General Electric Company at Pittsfield, Mass., and later transferred to the transformer department. In 1927 he was selected as manager of the holding company division of the central station department, and in 1933 he became manager of the customer division. Mr. White was a member of the Institute for a time, having been elected an Associate in 1919, and was at one time chairman of the Pittsfield Section.

Former President of Franklin Institute Dies. Dr. Walton Clark, formerly vice president of the United Gas Improvement Company and formerly president of the

Franklin Institute of Pennsylvania, died at his home in Chestnut Hill, Pa., on July 30, 1934, after a long illness. He was born in Utica, N. Y., in 1856, and entered the gas industry at the age of 17. He held positions with various properties, until he entered the United Gas Improvement Company in 1888. He became vice president in 1903, and retired 11 years ago, becoming consulting engineer. Dr. Clark was elected president of the Franklin Institute in 1907 and held office for 17 years. He was a past-president of the American Gas Light Association and of the American Gas Institute. Until recently he was a member of the Institute, having been elected Associate in 1908 and Member in 1911, resigning in April 1934.

Engineering Foundation

Engineering Foundation Pays Tribute to Founder Swasey

To PAY fitting tribute to Ambrose Swasey of Cleveland, Ohio, upon the 20th anniversary of his creation of The Engineering Foundation, and in celebration of his approaching (December) 88th birthday, some 67 engineers, industrial leaders, educators, and scientists assembled for dinner at the Union League Club, New York, N. Y., Thursday evening, October 18, 1934, with Mr. Swasey present as the guest of honor.

In opening the ceremonies, H. P. Charlesworth, chairman of The Engineering Foundation, and past-president of the Institute, paid high tribute to Founder Swasey and spoke appreciatively also of the tireless, long-time services of Director Alfred D. Flinn. The 4 speakers scheduled for the program included Dr. Frank B. Jewett, former vice chairman of The Foundation, and past-president of the Institute; Dr. Michael I. Pupin, second chairman of The Foundation, and past-president of the Institute; Dr. Karl Taylor Compton, president, Massachusetts Institute of Technology, Boston; and Harold V. Coes, president, United Engineering Trustees, Inc., and past-president of The American Society of Mechanical Engineers. Circumstances, however, prevented the attendance of Doctor Pupin and Mr. Coes.

Dr. Jewett Outlines Unique Characteristics

Doctor Jewett in his brief address emphasized the unique character of The Engineering Foundation, in that it is the only one dedicated wholly to the furtherance of the engineering profession and its contribution to human welfare, and in that the charter under which Mr. Swasey created the Foundation provides a latitude and flexibility that will enable it to serve effectively and indefinitely in spite of constantly changing conditions.

Doctor Jewett cited also that Foundation is: unique in having charter provisions for a governing board that definitely is not self-perpetuating, but made up of members elected independently and periodically by the participating technical societies, and in having absolute authority over Foundation's destinies placed in this board even during the continuing life of the founder; unique in its coöperative relations with the participating societies; truly great, not so much for the money it has available for expenditure, but in that it gives the engineering profession a definite medium through which to make lasting contributions for the benefit of mankind; the very essence of a true democracy, created and inspired by a great and typically American citizen.

Dr. Compton Indicates Opportunities

Doctor Compton, in discussing briefly some of Foundation's future opportunities for effective public service, gave 3 important suggestions: (*a*) the development of qualified research men and, later, the development and expansion of research fields; (*b*) the fostering of important new technical and scientific projects; (*c*) the fostering and further development of coöperative engineering and scientific research projects.

With reference to the development of men, Doctor Compton emphasized the fact that the national research fellowships available in recent years have been largely responsible for the improved scholarship that is beginning to enable the United States to take its proper place in important scientific fields such as, for instance, theoretical and mathematical physics. With reference to new projects, Doctor Compton cited the well-known growth or "fly" curve, as representing also the stages of development of an idea or of an enterprise, stating that Foundation might to very good advance "nurse forward-looking projects through the initial stages of slow development and toward the stages of established public acceptance and consequent self-support."

With reference to coöperative projects, Doctor Compton pointed out that they were of ever increasing importance as society becomes more complex, and that The Engineering Foundation could do an important work by supplying the vision and fundamental organization required to get such projects actually under way. As an example of this latter, he cited the Engineers Council for Professional Development that has been created and is being promoted "to care for some of the problems facing engineers individually and as organized groups," in which Engineering Foundation is assisting. Another example cited was the coöperative study of soil and foundation problems, looking toward a better understanding of the facts and the development of a better technique.

Chairman Charlesworth Presents Citation

As the closing feature of the inspiring occasion, Chairman Charlesworth first read and then presented to Mr. Swasey, a parchment document bearing a statement befitting the occasion and carrying the personal signature of each person present. The text of this memento follows:

To Ambrose Swasey, Founder: On this happy occasion, officers of the American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, American Institute of Electrical Engineers and of kindred technical societies and associations of scientists together with present and former members of United Engineering Trustees, Inc., and of The Engineering Foundation, and other friends, have gathered to celebrate the 20th anniversary of The Engineering Foundation and to honor you as the one whose foresight and generosity brought about in 1914 the establishment of that unique and beneficent institution.

To you the fraternities both of engineers and of scientists express high esteem as one of their most beloved members and generous benefactors.

In the 20 years since you made your first gift, there has been a steady growth in appreciation of your great conception of an institution through which the coöperative activities of engineers, scientists, and industrialists could contribute by research and in other ways to the advancement of the profession of engineering and the good of mankind. Great have been its contributions; they mark but the beginning of far greater service in the future.

For your 88th birthday 2 months hence, we wish you health and happiness and assure you of our gratitude and abiding affection. May many succeeding birthdays bring you the satisfaction of witnessing the accelerated growth and increasing usefulness of your great undertaking, The Engineering Foundation!

Those present and who signed the foregoing testimonial were:

For the American Chemical Society, L. H. Baekeland.

For the American Institute of Electrical Engineers, H. H. Barnes, Jr., W. S. Barstow, O. E. Buckley, H. P. Charlesworth, E. H. Colpitts, H. B. Gear, Bancroft Gherardi, H. H. Henline, G. R. Henninger, F. B. Jewett, J. A. Johnson, P. B. Juhnke, G. L. Knight, F. J. Meyer, H. H. Porter, E. W. Rice, Jr., C. E. Skinner, W. I. Slichter, R. W. Sorensen, L. B. Stillwell, W. H. Timbie, J. B. Whitehead, and H. R. Woodrow.

For the American Institute of Mining and Metallurgical Engineers, G. D. Barron, G. H. Clevenger, A. S. Dwight, H. G. Moulton, T. T. Read, J. V. W. Reynders, R. M. Roosevelt, A. J. Wadhams, and T. H. Wickenden.

For the American Society of Civil Engineers, O. H. Ammann, J. V. Davies, O. E. Hovey, C. W. Hudson, H. deB. Parsons, G. H. Pegram, J. H. Perry, Robert Ridgway, G. T. Seabury, F. L. Stuart, and A. S. Tuttle.

For The American Society of Mechanical Engineers, W. L. Abbott, W. L. Batt, C. E. Davies, H. N. Davis, W. S. Finlay, Jr., E. R. Fish, D. S. Jacobus, G. A. Orrok, R. I. Rees, G. A. Stetson, R. V. Wright, and D. R. Yarnall.

For The Engineering Foundation, A. D. Flinn, and J. T. Grady.

For the Franklin Institute, Howard McClenahan.

For the Rockefeller Foundation, Max Mason.

For the United Engineering Trustees, John Arms.

Miscellaneous, Herman Aaron, Parker and Aaron, Charles A. Baker, P. E. Bliss, Warner and Swasey, K. T. Compton, Massachusetts Institute of Technology, and H. W. Craver, Engineering Societies Library.

Conference Groups in Business Planned

A plan to organize permanent conference groups of executives in business and industry is announced by the Personnel Research Federation. Developed to meet the new problems which are being created by rapid economic, governmental, social, and technological changes, the plan aims to establish and to maintain bases for harmony in employee relations. Each conference group will be composed of the highest ranking personnel executive from 12 to 20 companies or institutions, and will meet monthly, or as often as may be necessary, to discuss common problems arising out of employer-employee relations. Groups will be formed in the principal centers of the country, conference participation involving no restriction upon independent action of members in their personnel activities.

The Personnel Research Federation was founded on the initiative of The Engineering Foundation in 1921; National Research Council and numerous other organizations interested in personnel coöperated. It is a federation of research and operating organizations and individuals organized for the purpose of bringing them into mutually beneficial coöperation in obtaining and applying knowledge about men and women at work in the widely varied activities of industry, commerce, government, and education. The industrial department of the Federation maintains a staff of investigators and research workers qualified in economics, statistics, engineering, and industrial psychology, and makes available to industrial members the latest studies of personnel problems contributed by leading universities and other research agencies as members or affiliates of the Federation.

Headquarters for the Personnel Research Federation are in the Engineering Societies Building, 29 West 39th Street, New York, N. Y.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Overcompounded D-C Generators in Parallel Without Equalizer

To the Editor:

The question of the operation of overcompounded d-c generators in parallel without an equalizer has been raised recently on several occasions. The problem is not of great practical importance, but it logically arises in a theoretical study of the parallel operation of d-c machines, and is discussed briefly in several textbooks. Unfortunately these texts are not in agreement, and as a consequence, many engineers are led into making an erroneous analysis of this problem and other related problems of primary importance.

In the text, "Direct Current Machinery" by Harold Pender, published by John Wiley and Sons, it is stated that if 2 overcompounded generators are operated in parallel and made to carry a given load with the equalizer removed and if the speed of one generator is increased, the current supplied by this generator will decrease and the current supplied by the other generator will increase. It is stated that this action will be accumulative so that all of the load will be shifted from the first generator to the other generator. Authors of several other texts hold that the contrary will occur.

At the annual convention of student Branches of the A.I.E.E. in the New York District held April 26, 1934, Sidney Rock and Erick Nelson, students at New York University, presented a paper based upon an experimental study which they contended disproved Professor Pender's statement. On the other hand, a "Letter to the Editor" published in the October 1932 issue of ELECTRICAL ENGINEERING, p. 745, by Professor Brainerd describes tests which he made that supported Professor Pender's view. It is the purpose of this letter to give a brief discussion which it is believed will clear up the points of disagreement.

Before going into the above problem, something should be said in general about the solution of such problems by graphical and analytical methods based upon steady state curves and steady state conditions. The change from one steady state point to another is always a transient change. In order for any graphical solution based upon steady state curves to apply and give correct results, it is necessary that the new operating point given by the curves, and all points between the initial and final steady state points, shall be stable points, and the final point must be a limit point toward which the transient change proceeds. Usually these conditions are properly fulfilled if the system is in stable operation over the parts of the curves involved. If there is any doubt, the transient change must be analyzed.

Now consider Fig. 1, which gives the wiring diagram of 2 overcompounded d-c generators operating in parallel without an equalizer, as described above. Assume that conditions are carefully adjusted so that the 2 generators are carrying a given load, indicated by points A and B in Fig. 2. Kirchhoff's law, which states that the sum of the voltages around a closed circuit must equal zero, holds at all times. Thus, while the current is steady, the sum of the induced voltages of the 2 armatures taken with the proper signs must equal the sum of the IR drops around the path *abcda* taken with the proper signs. If the induced voltage of generator 1 is suddenly increased by any means, Kirchhoff's law still holds, and therefore the sum of the drops must increase. Since there is inductance in the armature and field windings, the current will not change instantaneously. At the first instant the current will be the same as before the increase in voltage of generator 1 occurred. The additional voltage required to make Kirchhoff's law hold comes from the circuit inductance times the rate of change of the current. This equals $-L\frac{di}{dt}$, where L equals the total effective inductance around the circuit *abcda*, and it is assumed that the load current does not change appreciably, at least at first. It will now be seen that the current must increase in the same direction as the increase in voltage in the circuit in order to make $-L\frac{di}{dt}$ of the proper sign. This shows definitely the direction of the initial change of current due to an increase in voltage of generator 1. Since both generators are overcompounded, the initial change in current will cause a further change in the same direction, and the action will be cumulative. These conclusions are in agreement with those reached by Messrs. Rock and Nelson, and contrary to those given by Professors Pender and Brainerd.

The discussion referred to in "Direct Current Machinery" by Pender is based upon the steady state voltage regulation curves given in Fig. 2.

Briefly, in Professor Pender's discussion the total load is represented by the length AB. If the voltage of generator 1 is increased to the value indicated by the dotted curve, it is argued that, since the total load would not change appreciably, the line current would necessarily be given by the line $A'B'$, and since $A'C'$ is less than AC, the current carried by generator 1 would

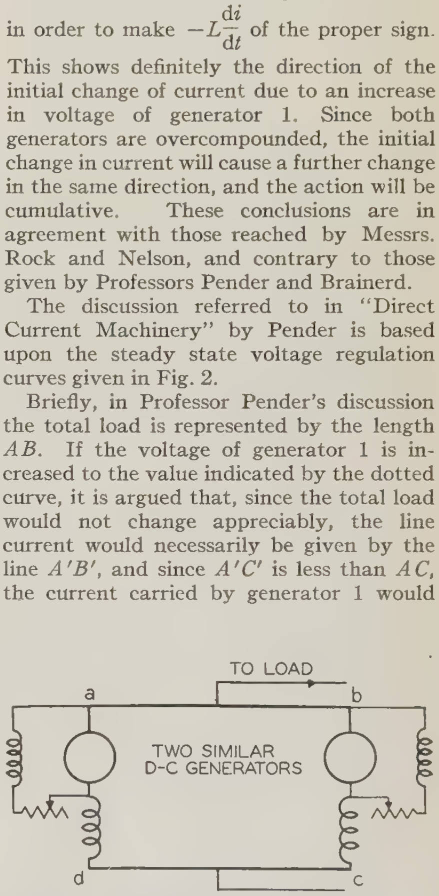


Fig. 1. Wiring diagrams for 2 overcompounded d-c generators in parallel without an equalizer

decrease. The unsoundness of this reasoning is now apparent. The points A' and B' are not stable points on the curves, and, as was shown, the transient change was not toward the points A' and B', but in the opposite direction. As a matter of fact, Professor Pender's method will in certain cases give a correct solution if the regulation curve of generator 1 is extended

sufficiently to the left and the curve for generator 2 is extended to the left in the motor region. Thus, in this case, the steady state curves give 2 solutions, and the transient analysis shows which is correct. Another point of interest is that during the transient change, the current and voltage changes do not follow the steady state curves because of the additional drops due to inductance which are not included in the steady state curves.

The actual transient solution of the current in the above problem showing how the current changes as a function of time is not difficult, but it is laborious and cumbersome if an attempt is made to take all factors into account. By making certain simplifying approximations, solutions may be obtained which are helpful in visualizing the manner in which the current changes.

As the simplest case, in Fig. 2 assume zero load current (each armature supplying only its shunt field current), constant shunt field currents, and constant speeds. Neglect the effect of mutual inductance between armatures and fields, and assume a straight line magnetization curve for each machine. Then, if the induced voltage of generator 1 is suddenly increased, the circuit conditions may be represented by the following linear differential equation:

$$L\frac{di}{dt} + Ri = Ki + E \qquad (1)$$

where

L = the sum of the self-inductances of the circuit *abcda*
R = the sum of the resistances around the circuit *abcda*
K = the resultant series magnetizing factor, which when multiplied by i gives the sum of the voltage changes due to the effects of the series fields and armature reactions
E = the difference of the 2 armature induced voltages set up by the shunt fields without the aid of the series fields, which difference, with the assumptions made, will be constant.

Set $R-K = N$; then eq 1 may be written

$$L\frac{di}{dt} + Ni = E \qquad (2)$$

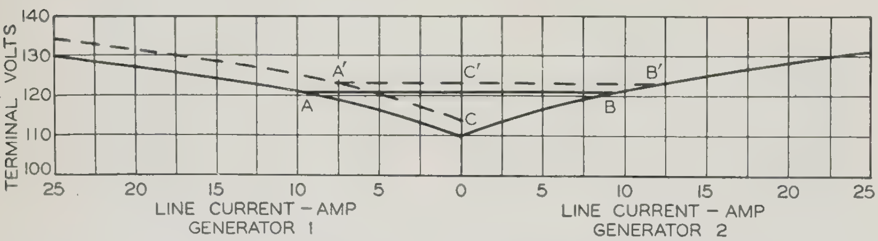


Fig. 2. Voltage regulation curves of 2 overcompounded d-c generators

Separating the variables and solving for i, there results

$$i = \frac{E}{N}\left(1 - \epsilon^{\frac{-Nt}{L}}\right)$$
$$= \frac{E}{R-K}\left(1 - \epsilon^{\frac{-(R-K)t}{L}}\right) \qquad (3)$$

When the machine is overcompounded, $K > R$; N is negative, and eq 3 becomes

$$i = \frac{E}{K-R}\left(\epsilon^{\frac{(K-R)t}{L}} - 1\right) \qquad (4)$$

Thus, with these approximations, the principal one being the neglect of saturation, a current curve is obtained which increases exponentially to infinity. The first part of the curve before saturation is reached should be reasonably close to the actual curve.

The problem is only slightly more involved if an initial load is assumed, but this solution will not be given here. If it is desired to take into account the effect of saturation, Froelick's equation may be used. The differential equation then becomes

$$L\frac{di}{dt} + Ri = [ai/(b + ci)] + E \qquad (5)$$

Clearing of fractions and collecting terms gives

$$(b + ci)L\frac{di}{dt} + (Rb-a-Ec)i + Rci^2 = Eb$$

Solving for $\frac{di}{dt}$ gives

$$\frac{di}{dt} = (K_1i^2 + K_2i + K_3)/L(b + ci) \qquad (6)$$

where

$K_1 = -Rc$
$K_2 = -Rb + a + Ec$
$K_3 = Eb$

Solving this differential equation gives

$$t = \int dt = \int\frac{L(b + ci)}{K_1i^2 + K_2i + K_3)}di + c' \qquad (7)$$

where C' is a constant of integration. With given values for the constants for any given machines, eq 7 may be evaluated by the use of ordinary integral tables. C' can be evaluated by means of the given initial conditions.

In conclusion it may be said that in many of the discussions of this problem there has been a failure to go back to the basic fundamentals involved. Also it should be pointed out that experimental results may be misleading where the set up is unstable and it is not clearly kept in mind that the problem is transient in nature. In an experimental problem of this character it is difficult to get the correct adjustments and values. Many times in such cases an analytical solution or analysis is more dependable than an experimental one. However, in 2 or 3 attempts, the writer has always checked experimentally the analytical conclusions given above for this problem.

Very truly yours,

O. W. Walter (M'29)
(College of the City of New York, N. Y.)

Information on Oliver Heaviside

To the Editor:

The fiftieth anniverary issue of Electrical Engineering (May 1934, p. 814) contained a biographical sketch of Oliver Heaviside and stated that no pictures existed of him. This is not correct, however, as several pictures have been published. An article by F. Gill in the *Bell System Technical Journal*, July 1925, p. 349, contains one picture. This particular picture is also


Oliver Heaviside (HM'18)

reproduced as a frontispiece in the 1925 edition of "Electrical Papers" published by the Copley Publishers of Boston.

In the October 1928 issue of *Electrical Communication* p. 71, is an article by Rollo Appleyard entitled "Pioneers of Electrical Communication—Oliver Heaviside." This contains several photographs of Heaviside and, in addition, views of the Heaviside family and of the family residence.

I am enclosing a copy of what seems to me to be the best of these pictures which I obtained from Mr. Appleyard 2 years ago and which, I feel, is desirable to publish in some future issue of Electrical Engineering."

Mr. Appleyard apparently went to considerable pains to learn the date of Heaviside's birth. From the records at the General Register Office, Somerset House, London, and the Town Hall Archives, Saint Pancras, London, he found the date and place recorded as May 18, 1850 and 55 King Street, Camden Town, London. The date given in the anniversary issue was 1848.

Very truly yours,

Carlton E. Tucker (A'22, M'28)
(Associate Professor of Electrical Engineering, Massachusetts Institute of Technology, Cambridge)

Editor's Note: The information given in the May 1934 issue of Electrical Engineering, while based upon a careful search of the available records, is apparently not correct, and we are glad to be able to submit that given above by Professor Tucker.

Personal Items

H. M. Turner (M'20) associate professor of electrical engineering, Yale University, New Haven, Conn., has been appointed chairman of the Institute's technical committee on communication for the year 1934–35. He was born at Hillsboro, Ill., in 1882 and studied electrical engineering at the University of Illinois receiving the degrees of B.S. in 1910 and M.S. in 1915. From 1910 to 1912 he remained at the university as an instructor, and then became an instructor at the University of Minnesota, where he organized courses in transient phenomena and radio. At the time of the war he was in charge of technical instruction of Signal Corps personnel, and came to the school for officer candidates at Yale University as assistant professor in 1918. In that year he was appointed an assistant professor of electrical engineering at Yale University, and was appointed associate professor in 1926, devoting his entire time to graduate instruction including courses in transient phenomena, wave propagation, and electronics, and directing research. Professor Turner has been a member of the Institute's committee on instruments and measurements since 1926, and of the communications committee since 1927. He is a member of the Institute of Radio Engineers, International Scientific Union, American Association for the Advancement of Science, Franklin Institute, Sigma Xi, and Eta Kappa Nu, and has published a number of papers in technical journals.

N. R. Stansel (A'03) industrial engineering department, General Electric Company, Schenectady, N. Y., has been appointed chairman of the Institute's committee on electrochemistry and electrometallurgy for 1934–35. He was born at Allenton, N. C., in 1877. After receiving the degree of B.S. from North Carolina State College in 1898 he remained as an instructor of physics for 3 years, then entered Cornell University for postgraduate work, receiving the degree of M.M.E. in 1903. He was employed by the Federal government for 8 years, then entered the a-c engineering department of the General Electric Company at Schenectady. He was subsequently transferred to the industrial sales and industrial engineering departments, and became manager of the office at El Paso, Tex. He returned to Schenectady in 1921 and has since been engaged in the industrial engineering department on work connected with electrochemistry and electrometallurgy. His book "Industrial Electric Heating" has recently been published. Mr. Stansel was a member of the general power applications committee, 1929–30, and has been on the committee on electrochemistry and electrometallurgy since 1930.

F. M. Farmer (A'02, F'13) vice president and chief engineer of Electrical Testing Laboratories, New York, N. Y., has been reappointed chairman for the year 1934–35 of the Institute's technical committee on research, of which he was chairman for part of the past year. A biographical sketch of Mr. Farmer is given in Electrical Engineering for February, 1934, p. 231, and a photograph on p. 1038 of the July 1934 issue. He has been a member of the research committee since 1929 and is also a member of the committees on power transmission and distribution and coördination of Institute activities. Recently he was elected vice chairman of the Standards Council of the American Standards Association.

C. M. Davis (A'08) engineer, transportation department, General Electric Company, Erie, Pa., has been appointed chairman of the Institute's technical committee on transportation for the year 1934–35. He was born at Chicago, Ill., in 1884 and completed the electrical engineering course at the University of Michigan in 1908, receiving the degree of B.S. The following year he received his master's degree from Union College, Schenectady, N. Y., and immediately entered the test department of the General Electrical Company there. Later he was assigned to the consulting engineering department, where he worked under Dr. Steinmetz. In 1913 he was transferred to the railway engineering department, becoming administrative assistant of the department in 1926. The department was moved to Erie in 1929, and Mr. Davis was named assistant engineer in 1930, the name of the department meantime having been changed to transportation department. Recently he was named engineer in charge.

M. E. Reagan (A'20, M'30) section engineer, automatic switching section, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been appointed chairman of the Institute's technical committee on automatic stations for the year 1934–35. He was born at Bridgewater, Iowa, in 1894 and after graduation from the University of Illinois in 1917 became inspector of substations for the Kansas City Railways Company, Kansas City, Mo. In 1920 he entered the employ of the "Westinghouse company as a design engineer on automatic and remote control of power and substations. Since 1927 he has been engineer in charge of automatic switching, supervisory control, and carrier current applications. He has been a member of the automatic stations committee of the Institute since 1929.

A. E. Logan (Enrolled Student) Proctor and Gamble Company, Cincinnati, Ohio, with his co-author S. W. Hannah (Enrolled Student) has been awarded the Institute's 1933 North Central District prize for Branch paper and has received honorable mention in the 1933 national awards for Branch paper for the paper entitled "The Measurement and Control of the Synchronous Machine Torque Angle." Mr. Logan was born at Marysville, Mo., in 1911 and moved to Colorado 10 years later. He received the degree of B.S. in E.E. from the University of Colorado in 1933. It was during his senior year that the prize winning paper was prepared. As holder of a fellowship he returned to the university for another year and received the degree of M.S. in E.E. in 1934.

J. C. Lincoln (A'07, F'32) chairman, board of directors, Lincoln Electric Company, Cleveland, Ohio, has been awarded the Samuel Wylie Miller medal of the American Welding Society in recognition of his contributions to the advancement of the science of electric fusion welding.

H. M. TURNER

N. R. STANSEL

M. E. REAGAN

C. M. DAVIS


R. W. GRAHAM


U.S. Bureau of Mines Photo
L. C. ILSLEY


W. F. DAVIDSON

Mr. Lincoln is one of the early pioneers of arc welding and has devoted most of his life to its research and development as an industrial tool. He is a graduate of Ohio State University, and was on the staff of C. F. Brush, inventor of the arc light, before joining the Elliott-Lincoln Electric Company, from which he formed the present company in 1896. It is reported that in 1916 he first used the electric arc in the structural field in the remodeling of an industrial structure; 3 years later the first motor redesigned from cast iron to arc welded steel was completed under his direction, and more recently he introduced the shielded arc. Mr. Lincoln has been a member of the electric welding committee of the Institute since 1927, and has served on 2 other committees.

L. C. Ilsley (A'14) supervising engineer, electrical section, U.S. Department of Commerce, bureau of mines experiment station, Pittsburgh, Pa., has been appointed chairman of the Institute's committee on applications to mining work. He was born at Thetford, Vt., in 1880, and studied at Worcester Polytechnic Institute, receiving the degrees of B.S. in 1903 and E.E. in 1905. Following short periods of time in the employ of the American Telephone and Telegraph Company and the General Electric Company he was employed by the Delaware, Lackawanna, and Western Railroad at Scranton, Pa., in 1906. Since 1910 he has been with the bureau of mines in connection with mine electrical safety work, and has been in charge of this work since 1918. Mr. Ilsley has written a number of technical papers on safety problems related to the use of electrical equipment in mines. He has been a member of the Institute's committee on applications to mining work since 1916, was a member of the safety codes committee from 1923 to 1927, and is now a member of the standards committee, on which he served from 1923 to 1932.

R. W. Graham (A'18, M'31) assistant electrical superintendent, Bethlehem Steel Company, Lackawanna, N. Y., has been appointed chairman for 1934-35 of the Institute's committee on applications to iron and steel production. He was born at Lindsay, Ont., Canada, in 1890 and emigrated with his parents to North Dakota in 1893. Following his graduation from the University of North Dakota in 1913 with the degree of E.E. he became an instructor in engineering at Cornell University for 3 years, and received the degree of M.E. in E.E. He then entered the electrical department of the Lackawanna Steel Company at Buffalo, N. Y. He entered the naval service in 1917 and was radio and communication officer of the U.S.S. "Arizona" at the time he returned to the Buffalo plant, which has since been absorbed by the Bethlehem Steel Company. In 1930 he was chairman of the Institute's Niagara Frontier Section.

W. F. Davidson (A'14, F'26) director of research, Brooklyn Edison Company, Brooklyn, N. Y., has been appointed chairman of the Institute's technical committee on electrophysics for the year 1934-35. He was born at Commonwealth, Wis., in 1890 and studied electrical engineering at the University of Michigan, from which he received the degrees of B.S. in 1913 and M.S. in 1920. In 1914 he entered the Westinghouse Electric and Manufacturing Company, but returned to the university 2 years later as an instructor. The war caused an interruption, and after 2 years service he returned in 1919, and became an assistant professor in 1920. In 1922 he resigned in order to organize research work in the Brooklyn Edison Company, with special reference to the problems of high voltage cables. This work was later expanded to include research and special testing activities in all fields of interest to the company. Mr. Davidson has been a member of Institute's research committee since 1925 and of the electrophysics committee since 1927, and is now secretary of the National Research Council's research committee for insulation.

N. B. Hinson (A'19, M'26) formerly assistant manager of operation, Southern California Edison Company, Ltd., Los Angeles, has been appointed chief engineer and chairman of the engineering committee of that company, reporting to the general manager. Mr. Hinson is a past-chairman of the Institute's Los Angeles Section.

W. M. Hoen (A'06, M'16) chief engineer, Ogleby Norton and Company, has recently returned from Moscow, U.S.S.R., where he has been since May 1930, and is now located at Hinsdale, Ill. For the first 2 years of this period he was chief engineer of a group sent to work on the iron mines, and after the completion of this work was engaged similarly on copper and gold mines and smelters, coming in contact with all the important mines of the U.S.S.R.

J. A. Cook (A'15, F'30) Lynn Gas and Electric Company, Lynn, Mass., has been appointed general manager of the company. He had been general superintendent of the electrical department for 9 years. Mr. Cook is a graduate of Massachusetts Institute of Technology, class of 1912, and was employed by the General Electric Company and the New York Edison Company before going to Lynn in 1925. He is a past-chairman of the Lynn Section of the Institute.

E. W. Judy (A'26) vice president and general manager, Duquesne Light Company, Pittsburgh, Pa., has been elected president of the Pennsylvania Electric Association. Mr. Judy has been identified with the public utility industry in Pennsylvania since he became superintendent of overhead lines of the Duquesne Light Company in 1923, previous to which he had been in western utilities. He was appointed operating manager of the company in 1927 and assumed his present duties 2 years later.

S. S. Hertz (A'17, M'27) has been appointed vice president and chief engineer of the Copperweld Steel Company, Glassport, Pa. Mr. Hertz is a graduate of Alabama Polytechnic Institute, class of 1911. Following employment with the Westinghouse Electric and Manufacturing Company and the Electrical Engineering and Manufacturing Company, he entered the Copperweld Steel Company in 1920, and became general sales manager in 1927.

P. M. Downing (A'98, M'08) first vice president and general manager, Pacific Gas and Electric Company, San Francisco, Calif., is a director of the Pacific Coast Electric Association. Mr Downing was a vice president of the Institute, 1925-27, and was on the power transmission and distribution committee, 1914-17 and 1927-28, and the power generation committee, 1928-29.

A. R. Schiller (A'20, M'27) vice president in charge of operations, Public Service Company of New Hampshire, Manchester, has been elected a vice president of the Twin State Gas and Electric Company to assume operation of the properties of that company which are located in New Hampshire. He will also continue the duties of his present position, to which he was elected in 1926.

B. L. Delack (A'11) formerly works manager, General Electric Company, Schenectady, N. Y., has been transferred to the staff of the vice president in charge of manufacturing and is devoting his time to the personnel problems of the company. Mr. Delack is a graduate of Clarkson College of Technology, and has been with the General Electric Company since 1903, becoming works manager in 1928.

JOHN FIES (A'28) Dallas, Texas, has recently been appointed chief engineer of the R. B. George Engineering Corporation, which engineers, finances, and constructs municipal and industrial power plants and electric systems in the southwestern states. Mr. Fies has been a member of the automatic stations committee of the Institute since 1931.

E. J. RUTAN (A'20, M'29) superintendent, test bureau, New York Edison Company, New York, has been elected secretary of the committee on electrical insulating materials of the American Society for Testing Materials. He has served on several committees of the Institute and is now a member of the instruments and measurements, and standards committees.

J. H. FOOTE (A'18, F'32) supervising engineer, Commonwealth and Southern Corporation, Jackson, Mich., has been elected secretary of the committee on copper wire of the American Society for Testing Materials. He has been a member of the Institute's committees on power transmission and distribution, 1929–31, and protective devices, 1932–34.

T. S. TAYLOR (M'21) professor of physics, Washington and Jefferson College, Washington, Pa., has been elected chairman of the committee on electrical insulating materials of the American Society for Testing Materials. He is also the Institute's representative on the committee on heat transmission of the National Research Council.

L. R. HICKS (A'12, M'28) electrical engineer, Gibbs and Hill, Rahway, N. J., is in charge of the engineering features of the cable installations in Baltimore, Md., and Washington, D. C., and other underground cable and conduit problems in connection with the electrification of the Pennsylvania Railroad.

W. C. BECKJORD (A'12) vice president and general manager, Boston Consolidated Gas Company, Boston, Mass., has resigned to become a vice president of the Columbia Gas and Electric Company with headquarters at New York, N. Y. He was formerly a vice president of the American Light and Traction Company, New York.

B. M. BRIGMAN (M'28) dean, Speed Scientific School, University of Louisville, Louisville, Ky., has been elected a manager for the year 1934–35 of the American Society of Mechanical Engineers. Dean Brigman is a member of the Institute's committee on legislation affecting the engineering profession.

J. D. WADDELL (A'32) Beaver, Pa., is in the engineering office of the western division of the Duquesne Light Company at West Bridgewater, Pa.

J. O. ROGERS (A'34) is operator in the power house of the Churchill River Power Company, Island Falls, Sask., Canada.

W. S. HILL (A'13, M'20) general superintendent, Grays Harbor Railway and Light Company, Aberdeen Wash., has been appointed chairman of the engineering and operation section of the Northwest Electric Light and Power Association.

R. D. DONALDSON (M'17) vice president, Utility Management Corporation, New York, N. Y., has recently been appointed representative, in the corporation, for all southern property groups in the Associated Gas and Electric System.

W. G. SCHNEIDER (A'23) engineer, Electric Auto-Lite Company, Toledo, Ohio, has been elected a vice chairman of the committee on nonferrous metals and alloys of the American Society for Testing Materials.

O. B. LYMAN (A'18, M'29) manufacturers agent, San Francisco, Calif., has been appointed northern California representative for the R. E. Uptegraff Manufacturing Company of Pittsburgh, Pa., manufacturers of a line of transformers.

W. G. H. FINCH (A'22, M'26) for the past 14 years chief engineer of the Hearst radio activities, has resigned to become assistant chief engineer of the Federal Communications Commission, Washington, D. C.

B. L. CONLEY (A'19, M'24) formerly chief engineer, Sunlight Electrical Manufacturing Company, Warren, Ohio, is vice president and treasurer of the Kingston-Conley Electric Company, Jersey City, N. J., manufacturs of fractional horsepower motors.

G. L. BASCOME (M'23) formerly sales engineer, National Valve and Manufacturing Company, Pittsburgh, Pa., has recently been appointed to the staff of the State Corporation Commission, Commonwealth of Virginia, Richmond.

C. C. KNOX (A'20, M'30) formerly in the engineering department, Byllesby Engineering and Management Corporation, Pittsburgh, Pa., is now in Shanghai, China, where he is employed by the Shanghai Power Company.

G. S. TIMOSHENKO (A'33) formerly teaching assistant in electrical engineering, University of Michigan, Ann Arbor, is in the department of electrical engineering at the Massachusetts Institute of Technology, Cambridge.

D. E. FOSTER (A'25) formerly chief radio engineer, General Household Utilities Company, Chicago, Ill., has joined the staff of the RCA License Laboratory, New York, N. Y.

CARL F. SCOTT (A'10, M'19) Pleasantville, N. Y., has been appointed engineer, appliance division, merchandise department, General Electric Company, Bridgeport, Conn.

E. F. H. MERCIER (M'20) director, Delegue de l'Union d'Electricite, Paris, France, has recently been elected president of the International Conference of Large Electricity Distribution Undertakings.

Obituary

FRANK JULIAN SPRAGUE (A'87, M'97, F'12, HM'32, past-president and member for life) died October 25, 1934, as this issue of ELECTRICAL ENGINEERING was going to press. A biographical sketch of Doctor Sprague is scheduled for inclusion in the next issue.

CALVIN WINSOR RICE (A'97, F'12) secretary, The American Society of Mechanical Engineers, New York, N. Y., died suddenly on October 2, 1934 from a cerebral hemorrhage. He was born at Winchester, Mass., on November 4, 1868, and received the degree of B.S. in electrical engineering from Massachusetts Institute of Technology in 1890. His first work was as assistant engineer of the Thomson-Houston Electrical Company at Lynn, Mass. When the company was absorbed by the General Electric Company he became an engineer in the power and mining department at Schenectady, N. Y. In 1895 he was sent to Cincinnati, Ohio, as district engineer for the company, but left shortly after to become electrical superintendent with the Silver Lake mines in Colorado. A year later he went to Montana as a consultant for the Anaconda Copper Mining Company, and then returned to New York where he held various engineering positions in the Kings County Electric Light and Power Company, Brooklyn, and the New York Edison Company, in which he was chief of the meter and testing department. Later he became vice president of the Nernst Lamp Company and a consulting engineer for the General Electric Company. Dr. Rice assumed the office of secretary of the A.S.M.E. in 1906, but he had already been active in engineering societies' work, for he participated in the first coöperative project of the 4 great national engineering societies, namely, the establishment of the John Fritz Medal. In 1902, as chairman of the Institute's building committee, he made efforts to secure a building primarily to house the Lattimer Clark library, the result of which was the gift by Andrew Carnegie of the Engineering Societies Building in New York. During this same year he suggested the plan of the Officers Reserve Corps and the Reserve Officers Training Corps to the chief of staff of the U.S. Army, and later assisted in working out the plan. Dr. Rice was a manager of the Institute, 1900–03, and a vice president, 1903–05. In 1926 he received the honorary degree of doctor of engineering from the Technische Hochschule in Darmstadt, Germany, and in 1932 became an honorary member of the A.S.M.E. Dr. Rice was a member of the Corporation of the Massachusetts Institute of Technology, and served as secretary and member

of the board of trustees of the New York Museum of Science and Industry. He held membership also in the American Association for the Advancement of Science and the American Committee of the World Power Conference, as well as in many organizations in Europe and South America. A medal of honor was awarded him at Cologne in 1931 by the Verein Deutscher Ingenieure in appreciation of his services in promoting mutual international interests of engineers.

George Herbert Harries (A'03, F'22, and member for life) Los Angeles, Calif., died on September 28, 1934. He was born at Haverfordwest, South Wales, on September 19, 1860. After varied experience as a printer, soldier, newspaper correspondent, and editor, he entered utility management when he became president of the Metropolitan Street Railway in Washington, D. C., in 1895. The following year he became president of the Washington Traction Company and associated companies, and in 1902 became vice president in charge of all construction and operation of the Washington Railway and Electric Company and controlled companies. In 1911 he became vice president of H. M. Byllesby and Company, management engineers of Chicago, Ill., and also president of the Louisville Gas and Electric Company, Louisville, Ky., and an officer of a number of companies throughout the country. He retired from the Byllesby Engineering and Management Corporation in 1930. During the war he was a major general, and was placed in command of a base section with headquarters at Brest, France. General Harries was president of the American Electric Railway Association in 1912–13, the Association of Edison Illuminating Companies in 1911–12, and the Illuminating Engineering Society in 1920–21. He was a member of The American Society of Mechanical Engineers, American Gas Institute, and other engineering societies.

Charles H. Wilson (A'91, M'92, and member for life) Mountain Lakes, N. J., formerly general manager of the long lines department of the American Telephone and Telegraph Company, died on September 30, 1934. He was born at Springfield, Ill., on February 13, 1861. After attending the schools in Quincy, Ill., he was employed by the Western Union Telegraph Company in Chicago, Ill., as an assistant electrician. Five years later, in 1881, he became assistant general superintendent of the Central Union Telegraph Company in Chicago. In 1888 he became superintendent of the Chicago Telephone Company, and in 1897 went to New York, N. Y., as general manager of the Southern Bell Telephone and Telegraph Company. He became general superintendent of the long distance lines department of the American Telephone and Telegraph Company in 1900, and general manager in 1915 of the same department, now renamed long lines. Mr. Wilson retired in 1919. Among the advances in which he took part were the laying of the first underground cables from New York to Philadelphia, enlarging use of leased lines by newspapers and press associations, and the inauguration, in 1915, of transcontinental service. During his career the number of telephones in use in the country increased from 71,000 to 11,800,000.

Elwood Grissinger (A'02, F'14) research engineer, Buffalo, N. Y., died on October 8, 1934. He was born at Mechanicsburg, Pa., on March 3, 1869, and received the degree of E.E. from Lehigh University in 1894. For 5 years he was employed by the Westinghouse Electric and Manufacturing Company, and was district engineer and salesman at Syracuse, N. Y., and Buffalo, N. Y. In 1899 he became a commercial engineer for several power companies at Buffalo, and in 1907 opened offices at Buffalo as a consulting mechanical and electrical engineer, where he designed electrical power systems for a number of manufacturing plants. He is credited with developing, about 1910, a relay telephone repeater for use in long distance transmission. The honorary degree of master of science was conferred upon him by Lehigh University for his work and discoveries in telephony.

Kikutaro Nogami (A'08) director, K. Nogami and Company, Osaka, Japan, died on August 1, 1934. He was born at Nishikunizaki on September 8, 1878, and was a graduate of the electrical engineering course at Tokio Imperial University. In 1903 he became chief electrical engineer of the Utsunomiya Lighting Company, and in 1905 became assistant electrical engineer at the Sumitomo Bessi Copper Mine, Iyo, Japan. He was appointed chief engineer in 1907, and later became identified with the company bearing his name.

Membership

Recommended for Transfer

The board of examiners, at its meeting held October 17, 1934, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Skinker, Murray F., asst. director of research, Bklyn. Edison Co., Bklyn., N. Y.

1 to Grade of Fellow

To Grade of Member

Alexander, Edward B., E.E., & asst. supt., elec. dept., N. Y. State Elec. & Gas Corp., Lockport, N. Y.
Anderson, Arvid E., engg. section, panel & equipment div., Gen. Elec. Co., Phila., Pa.
Brown, Vincent J., elec. sales engr., J. Leo Scanlon Co., Syracuse, N. Y.
Carpenter, Charles B., engr., Pacific Tel. & Tel. Co., Portland, Ore.
Cory, Harold M., elec. engr., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Darrin, Ralph M., mgr., central station dept., Gen. Elec. Co., Buffalo, N. Y.
Dewey, Glen H., sales engr., Gen. Elec. Co., Buffalo, N. Y.
Eighmy, George W., sales engr., central station dept., Gen. Elec. Co., Buffalo, N. Y.
Fisher, Benjamin A., assoc. prof. of E.E., Okla. A. & M. Col., Stillwater.
Freudenberger, Philip D., designing engr., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Geary, Elmer A., chargeman, elec. drawing room, N. Y. Shipbuilding Co., Camden, N. J.
Hamilton, James H., assoc. prof. of E.E., Univ. of Utah, Salt Lake City.
Harder, Edwin P., engr.-elec., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Humphries, Powell H., asst. prof. of E.E., Tulane Univ., New Orleans, La.
Kramer, Andrew W., assoc. editor, *Power Plant Engg.*, Chicago, Ill.
Morris, Benn G., E.E., Gen. Elec. Co., Buffalo, N. Y.
Oglebay, Wm. J., supt. of distribution dept., Buffalo Gen. Elec. Co., Buffalo, N. Y.
Piasecki, Harry A., E.E., Buffalo Gen. Elec. Co., Buffalo, N. Y.
Pollard, George M., asst. supt. of operation, Buffalo Gen. Elec. Co., Buffalo, N. Y.
Rockwood, George H., member tech. staff, Bell Tel. Labs., Inc., N. Y. City.
Steeb, George, Relay Engr., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Townend, Harold L., E.E., Gen. Elec. Co., Buffalo, N. Y.
Veinott, Cyril G., E.E., Westinghouse E. & M. Co., Springfield, Mass.
Vidal, Henri B., sales engr., Westinghouse E. & M. Co., Niagara Falls, N. Y.
Werly, Berlyn M., E.E., Eastman Kodak Co., Rochester, N. Y.
Wing, Lesher S., chief engr., western div., Nat. Pwr. Survey, Federal Pwr. Comm., San Francisco, Calif.
Young, Wm. M., research engr., Taylor Instrument Companies, Rochester, N. Y.

27 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before Nov. 30, 1934, or Jan. 31, 1935, if the applicant resides outside of the United States or Canada.

Andreasen, I. A., Interborough Rapid Transit Co., N. Y. City.
Apsley, W. J. E. (Member), Pa. Water & Pwr. Co., Baltimore, Md.
Atkinson J. (Member), Westinghouse Elec. & Mfg. Co., Buffalo, N. Y.
Boyce, C. W. (Member), Niagara, Lockport & Ontario Pwr. Co., Medina, N. Y.
Boyles, R. G. (Member), So. Calif. Edison Co. Ltd., Los Angeles.
Brown, E. A. (Member), Westinghouse Elec. & Mfg. Co., Buffalo, N. Y.
Brown, H. J., Lear Developments, N. Y. City.
Brown, L. K., N. Y. State Elec. & Gas Corp., Lancaster.
Brown, R. LeC., Consolidated Ashcroft Hancock Co., Boston, Mass.
Bunting, G. M., Mich. Bell Tel. Co., Saginaw.
Chaffin, R. B., Va. Elec. & Pwr. Co., Fredericksburg.
Cleveland, T. C., Niagara, Lockport & Ontario Pwr. Co., Olean, N. Y.
Cole, B. T., Westinghouse Elec. & Mfg. Co., Buffalo, N. Y.
Collamore, C. T., Bklyn. Edison Co. Inc., Bklyn, N. Y.
Colvin, A. L. (Member), Niagara, Lockport & Ontario Pw. Co., Angola, N. Y.
Coombs, D. S., 1125 Ellis St., San Francisco, Calif.
Cooper, D., Canadian Industries Ltd., Brownsburg, Que., Can.
Cornell, O. K. (Member), Lockport, Newfane Pwr. & Water Co., Newfane, N. Y.
Coryell, R. W., Rochester Gas & Elec. Corp., Rochester, N. Y.
DeBoer, D. J., Harza Engg. Co., Columbus, Neb.
Decker, G. E., So. Calif. Edison Co. Ltd., Los Angeles.
Deckman, G. C. (Member), Niagara, Lockport & Ontario Pwr. Co., Olean, N. Y.
Felton, C. H. (Member), Springville Municipal Lt. & Pwr. Plant, Springville, N. Y.
Ferguson, D., N. Y. Hospital, N. Y. City.
Fisher, E. C., Okla. Gas & Elec. Co., Harrah.
Friedrich, H. L., Westinghouse Elec. & Mfg. Co., Houston, Texas.
Gehring, M. C., Am. Tel. & Tel. Co., Toledo, Ohio.
George, G. C. (Member), N. Y. Pwr. & Lt. Corp., Albany.
Gienger, J. A. (Member), Eastman Kodak Co., Rochester, N. Y.
Gohlke, A. C., Cleveland Elec. Illum. Co., Berea, Ohio.
Gonseth, J. E. (Member), Automatic Elec. Co., Chicago, Ill.
Hammar, S. J., Wash. Water Pwr. Co., Spokane.
Harden, J. G., Ind. Bell Tel. Co., Indianapolis.
Hardy, J. R. G., 205 E. 78th St., N. Y. City.
Hayden, C. C., Southern Pacific Co., Oakland, Calif.

Herbein, R. C., Allentown High School, Pa.
Herr, M. D., Wash. Water Pwr. Co., Spokane.
Hoeke, F. A. (Member), Gen. Elec. Co., Birmingham, Ala.
Horner, R. S., Am. Steel & Wire Co., Worcester, Mass.
Ide, G. W. (Member), Niagara, Lockport & Ontario Pwr. Co., Medina, N. Y.
Ingersoll, N. A. (Member), Niagara, Lockport & Ontario Pwr. Co., Angola, N. Y.
Jaeger, H. K. (Member), Robertson Elec. Constr. Co., Buffalo, N. Y.
Keiller, T. M. (Member), El Paso Elec. Co., El Paso, Texas.
Kennelly, D. J., So. Calif. Edison Co. Ltd., Los Angeles.
Leader, C. C., Gen. Elec. Co., Schnectady, N. Y.
Malti, M. G. (Member), Cornell Univ. Ithaca, N. Y.
Manz, O. W. Jr. (Member), Bklyn. Edison Co., Inc., Bklyn., N. Y.
Martsolf, C. M., Bell Tel. Co. of Pa., Pittsburgh, Pa.
McCallum, J. R. (Member), N. Y. State Elec. & Gas Corp., Lancaster, N. Y.
Moore, E. R., Ind. Bell Tel. Co., Indianapolis.
Morreall, H. W., Kulpmont Steam Elec. Station, Mt. Carmel, Pa.
Olney, D. H., Wash. Water Pwr. Co., Spokane.
Parker, W. P. (Member), Board of Water & Elec. Commissioners, Dunkirk, N. Y.
Peters, E. G., Wash. Water Pwr. Co., Spokane.
Pingree, G. N., Gen. Elec. Co., Dallas, Texas.
Pittenger, H. W. (Member), Westinghouse Elec. & Mfg. Co., Buffalo, N. Y.
Poesl, J. A. (Member), E. I. du Pont ed Nemours & Co., Inc., Niagara Falls, N. Y.
Popp, E. W. (Member), Buffalo Genl. Elec. Co., N.Y.
Provenzano, C. J., Buffalo Gen. Elec. Co., N. Y.
Raneri, R., P. W. A. Dept. of Interior, Washington, D. C.
Robison, H. H., Dallas Pwr. & Lt. Co., Texas.
Rouse, A. F. (Member), N. Y. & Queens Elec. Lt. & Pwr. Co., L. I. City, N. Y.
Schelkunoff, S. A. (Member), Bell Tel. Lab., N. Y. City.
Sellers, J. F., Allis Chalmers Mfg. Co., W. Allis, Wis.
Smedberg, J. W. (Member), Board of Pub. Utilities, Jamestown, N. Y.
Snavely, H. E., N. Y., N. H., & H. R. R. Co., Bronx, N. Y. City.
Spence, S. R., Canadian Nat. Carbon Co., Toronto, Ont., Can.
Spicer, M. S., Chesapeake & Potomac Tel. Co. of Va., Richmond.
Sukachoff, A. (Member), City of N. Y., N. Y. City.
Swindell, G. R., Humble Oil & Refining Co., Baytown, Texas.
Wachtel, C. P. (Member), Robertson Elec. Const. Co., Buffalo, N. Y.
Walker, C. P., City Office, Tallahassee, Fla.
Ward, R. P., A. & M. Coll. of Texas, College Station, Texas.
Weagraff, C. R. (Member), Water & Lt. Dept., City of Salamanca, Salamanca, N. Y.
White, C. W., So. Calif. Edison Co. Ltd., Los Angeles.
White, P. A., Pa. Pwr. & Lt. Co., Shenandoah, Pa.
Whittemore, L. E. (Member), Am. Tel. & Tel. Co., N. Y. City.

77 Domestic

Foreign

Haddow, A. B. (Member), Municipal Board, Naini Tal, United Provinces, India.
Whyte, W L., Ceara Tramway, Lt. & Pwr. Co. Ltd., Fortaleza, Ceara, Brazil, S. A.

2 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Adams, William C., 801 S. Lynn St., Champaign, Ill.
Babloozian, Levon M., 776 N. Cass St., Milwaukee, Wis.
Gosinski, John N., Consumers Pwr. Bldg., Jackson, Mich.
Jordan, Henry, 7408A Christopher Columbus, Montreal, Que., Can.
Losoncy, William A., 14067 Cherrylawn Ave., Detroit, Mich.
Marks, Louis Wendell, 625 McClellan St., Schenectady, N. Y.
Roisland, Kornelius, 356 W. 34th St., N. Y. City.
Schultz, Carl H., 15 Cook St., Jersey City, N. J.
Simpson, Sidney, Deputy Loco. Supt., Eastern Bengal R. R., Kanchrapara, Bengal, India.
Spiegel, Wm. F., 116 Bergen Ave., Jersey City, N. J.
Stuntz, Hans, 106 Peck Ave., Newark, N. J.
Wagoner, K. S., 320 Wisconsin, Oak Park, Ill.

12 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

ALLGEMEINE METALLKUNDE. By E. Piwowarsky, Berlin, Gebrüder Borntraeger, 1934. 248 p., illus., 10x7 in., paper, 14.40 rm.; bound, 15.80 rm. The main divisions of general metallography are discussed in this text in easily understood fashion, with emphasis upon general laws and basic relationships. The structure of metals, alloys, the properties of molten metals, solidification, solubility of gases in metals, mechanical and physical properties, crystallization and recrystallization, hardening and heat treating, and corrosion are considered.

ALTERNATING CURRENTS. By A. E. Clayton. N. Y. and Lond., Longmans, Green & Co., 1934. 334 p., illus., 9x6 in., cloth, $4.50. A textbook for students of electrical engineering which covers the essentials concisely, with emphasis throughout upon principles. The book covers the work usually done by second and third year students in English universities.

ARSENICAL and ARGENTIFEROUS COPPER. By J. L. Gregg with a foreword by H. Foster Bain. N. Y., Chemical Catalog Co., 1934. 189 p., illus., 9x6 in., cloth, $4.00. After an historical introduction and a valuable chapter upon the general properties and uses of copper, the book discusses the metallurgy of arsenical and argentiferous copper, its constitution, electrical, thermal, and mechanical properties, the corrosion of arsenical copper and brass, and the uses of arsenical copper. A good bibliography is included. The book is an exhaustive and authentic summary of existing knowledge of these coppers.

BILDWORT ENGLISCH. Technische Sprachhefte 11, MANAGEMENT. Berlin, VDI-Verlag, 1934. 33 p., illus., 8x6 in., paper, 1.50 rm. This pamphlet is one of a series intended to assist German-speaking engineers to read English, especially engineering English. This number is devoted to management. A brief outline of that topic is given in the English language, in which the greatest possible number of technical terms is introduced.

ELECTRICAL COMMUNICATION. By A. L. Albert. N. Y., John Wiley & Sons, 1934. 448 p., illus., 9x6 in., cloth, $5.00. A college text in communication engineering which treats all branches of wire and wireless telegraphy and telephony in their relations with each other in modern systems. The broad engineering features of communication apparatus and plant are described, with the object of providing a basic training. Numerous references to original papers accompany each chapter.

Die KOSTEN der LICHTBOGENSCHWEISSUNG. By F. von Meier. Berlin, VDI-Verlag, 1934. 32 p., illus., 8x6 in., 1.90 rm. This pamphlet reviews the elements that enter into the cost of arc welding and discusses the amount that each contributes to the total cost. Curves are given which enable the welding engineer to determine costs quickly and accurately for all ordinary classes of work.

LOGARITHMS NUMERICAL and GRAPHICAL for the Easy and Accurate Calculation of Commercial and Technical Problems. By N. R. Corke. Lond., Gee & Co. Ltd., 1934. 79 p., illus., 11x8 in., cloth, 8s 6d. This book, which is adapted to self study, is intended to equip the reader to use logarithms readily in technical and commercial calculations. The 4 chief practical applications of logarithms, the table, slide rule, logarithmic graph paper, and alignment chart, are explained and their uses for a variety of purposes illustrated. The book is unusually clear and practical, and calls for little mathematical knowledge.

RADIO RECEIVER MEASUREMENTS. By R. M. Barnard. Lond., Iliffe & Sons, Ltd., 1934. 116 p., illus., 8x5 in., cloth, 4s 6d. Modern methods for measuring the selectivity, sensitivity and fidelity of radio receivers are presented in detail, and the interpretation of tests in estimating receiver performance is discussed. The book is intended primarily for radio service engineers, but will also be useful to amateurs. The standards proposed are in general those of the Institute of Radio Engineers.

RECOMMENDED ENGINEERING DRAWING PRACTICE. By Institution of Engineers, Australia, Science House, Gloucester and Essex Sts., Sydney, N.S.W., 1934. 128 p., illus., 10x6 in., cloth, 4s 6d. This volume is nominally a second edition of "Mechanical Drawing Standards," published by the Institution in 1926. The work has, however, been extended to embrace the drawing practice of all the main branches of engineering and has been rewritten and revised. It is offered as a code, intended to promote uniformity of practice throughout the Commonwealth.

Les COORDONNÉES SYMÉTRIQUES en ÉLECTROTECHNIQUE. By A. Iliovici. Paris, J. B. Baillière et Fils, 1934. 284 p., illus., 8x5 in., cloth, 38 frs. Although the literature upon the application of the method of symmetrical coordinates to electric circuit problems has become voluminous in recent years, there are practically no books giving a general survey of the subject. This lack the present book aims to fill. It presents the principles of the method, explains the fundamental formulas, and shows how they are applied to the solution of problems of unbalanced polyphase circuits.

NATIONAL PHYSICAL LABORATORY, REPORT for the YEAR 1933. London, His Majesty's Stationery Office, 1934. 264 p., illus. 11x8 in., paper, 13s. (Can be obtained from British Library of Information, New York, N. Y., $3.50.) The report reviews the work done during 1933 by the various departments of the Laboratory. The important investigations in the fields of electricity, engineering, metallurgy, aerodynamics, physics, etc., are described in some detail, and a list of papers published by the staff is included. As a guide to the work done and in progress, the book will be useful to research workers and engineers in many lines.

Das WELTFERNSPRECHEN. Vortragsreihe des Elektrotechnischen Vereins in Gemeinschaft mit dem Ausseninstitut der Technischen Hochschule Berlin. Edit. by F. Lubberger. Munich & Berlin, R. Oldenbourg, 1934. 85 p., illus., 10x7 in., paper, 4.50 rm. A series of lectures, delivered last winter before the German Society of Electrical Engineers, dealing with the problems of international telephony. The history and organization of international service, the technique of international telephony and its economic importance are discussed by several authorities.

THEORIE der ELEKTRIZITÄT. Bd. 1: Einführung in die Maxwellsche Theorie der Elektrizität. By R. Becker. 10 ed. Leipzig & Berlin, B. G. Teubner, 1933. 265 p., illus., 9x6 in., cloth, 14.50 rm. This volume is a new edition of Becker's revision of the well known Abraham-Föppl "Introduction to Maxwell's Theory of Electricity," which first appeared in 1894 and has been one of the most popular texts. The new edition contains a series of revisions and additions which incorporate recent developments and improvements.

Engineering Societies Library

29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

Laytex, an Unusual Dielectric, Is Announced.—Announcement has been made by the United States Rubber Company of a new type of electrical insulation, called Laytex, which possesses a number of unusual qualities. Its principal application so far has been as a covering for wires, and it is believed by the manufacturer that its superior properties will require in time that all existing codes and specifications on wire insulation will have to be rewritten. It is claimed that of all known flexible insulation, Laytex is the most flexible, has the highest tensile strength and resistance to compression, and has the highest dielectric strength and insulation resistance. Because of these qualities, it permits thinner but superior walls which in turn make possible finished conductors lighter in weight and smaller in bulk. In certain applications, a reduction of 25 per cent in the outside diameter, and 50 per cent in the weight of the conductor are effected.

Laytex is derived directly from latex, the milk of the rubber tree. It is a noncoagulated, nonmilled dielectric, purified to remove proteins, sugars, and water solubles. It is maintained in its natural liquid state until the very last manufacturing process, which converts it into a solid dielectric, perfectly and uniformly applied upon a conductor by the dip or pass method. This method consists of running a conductor through a series of baths of liquid, depositing upon the conductor, with each dip, a film of dielectric which is almost immediately converted from liquid to solid. As the conductor travels vertically, any excess liquid flows back into the container. No mechanical support touches the insulation until it has become solidified.

Physical Characteristics. Physical characteristics of Laytex, as determined by tests, show that it has a tensile strength of 5,000 lb per sq in., an elongation at rupture of 750 per cent, and a set in a 2-in. gauge length of $^1/_4$ in. It will be observed that the tensile strength approaches that of nonflexible insulation, and it may be possible to adapt it to service conditions where metallic coverings are now necessary.

Electrical Characteristics. Tests on the electrical characteristics show that it has a dielectric strength of 800 volts per mil; an insulation resistance constant, $K = 54{,}000$, in the formula $R = K \log_{10} D/d$ where R is the insulation resistance in megohms per 1,000 ft, D is the diameter over the insulation, and d is the diameter of the copper conductor. It will be noted that the insulation resistance constant is more than twice as high as that of the best grade of rubber compound required by the A.S.T.M. specifications.

Moisture Absorption. The amount of water or moisture absorbed by Laytex after soaking in water, as determined by the change in specific inductive capacity, is stated to be remarkably low. Values specified are: (*a*) Specific inductive capacity after one day in water shall not exceed 4; (*b*) increase in specific inductive capacity from end of first to end of 14th day shall not exceed 10 per cent; and (*c*) increase in specific inductive capacity from end of 7th to end of 14th day shall not exceed 4 per cent.

Successful applications of this new dielectric have already been made during the development period in many fields. It has been thoroughly proved for a number of different uses, including emergency telephone wire, nonmetallic underground cables, portable cord, switchboard wire, and radio wire. The future of Laytex, in the opinion of the manufacturer, offers possibilities much too great for prediction.

General Cable Appointment.—According to a recent announcement, George Sherry has been appointed General Sales Manager of the General Cable Corp., New York.

Large Order to Delta-Star.—The Bureau of Power and Light, Los Angeles, has awarded a $140,889.00 contract to the Delta-Star Electric Co. of California, Los Angeles, covering sixteen 287,000-volt, 1,200-ampere, 3-pole motor operated disconnecting switches for installation on the 275,000-volt, double circuit transmission line connecting Los Angeles with Boulder Dam. These switches, designed in Chicago, will be manufactured in Los Angeles by Kelman Elec. & Mfg. Co., with whom Delta-Star has made manufacturing arrangements for production of Delta-Star designs in the western territory. According to the announcement the 287-kv switches, known as MR-239, will be the largest yet produced in this country.

Small Motor With Speed Reducer.—The Dunmore Company, Racine, Wis., announces a new motor with built-in speed reducer—type, K3-M, $^1/_7$-hp, equipped with a single gear reduction unit capable of carrying the full power of the universal type motor. Three gear ratios can be supplied from stock—5:1, $14^1/_2$:1, and 34:1, giving shaft speeds of 1,300, 448, and 191 rpm, respectively. The motor has a forced air ventilating system making it suitable for continuous duty.

New Fuses.—The Littelfuse Laboratories, 4507 Ravenswood Ave., Chicago, Ill., announces the latest addition to its specialized fuse family—"Tattelites." Tattelites are a line of neon discharge tubes having breakdown potentials of 100, 250, 500, 1,000, and 2,000 volts. They are really "voltage" fuses, protecting equipment against excessive voltages, whereas regular fuses protect against excessive currents. They operate by shunting out the overload. Applications are numerous; they prevent insulation breakdowns; protect voltmeters, ammeters, transformers, condensers, and gaseous rectifiers against voltage surges; make good radio lightning arresters, leak-off static charges from machinery; test for blown fuses, defective resistors, and condensers; indicate radio frequency, resonance peaks, high tension lines; and are used in making bleeders for d-c power supplies, etc. Tattelites are described in the new Littelfuse catalog No. 6.

Condensers for Condenser-Start Motors.—A wide variety of both electrolytic and oil-filled condensers for condenser-start motors is announced by the Aerovox Corporation, 82 Washington St., Brooklyn, N. Y. Obtainable in round rubber insulated or standard cans, and in rectangular cans with or without insulating jackets, any desired terminals, the electrolytic units offer large capacities at moderate cost. Hermetically sealing effectively prevents evaporation or absorption so that moisture content remains stable throughout long life. Special composition spacer—an exclusive Aerovox feature—protects units against surges. Internal metal parts are entirely of aluminum, eliminating electrochemical action and corrosion, and the containers are leak and seepage proof. Approximately three-quarters of a million of these units have been placed in service during past few years. Oil-filled units are intended for condenser-transformer motors and power factor correction, and are available in round and rectangular containers, various sizes and shapes and terminal arrangements. Each unit comprises a thoroughly dehydrated, oil-impregnated section in oil bath, encased in hermetically-sealed metal container.

Trade Literature

Asbestos Magnet Wire.—Bulletin, 6 pp. Describes round, square, and rectangular asbestos insulated magnet wire. General Cable Corp., 420 Lexington Ave., New York.

Luminous-Tube Transformers.—Bulletin GEA-1305C, 36 pp. Describes various types of transformers used in the operation of luminous-tube signs. General Electric Co., Schenectady, N. Y.

Grease and Oil Seals.—Catalog 25, 16 pp. Describes a new oil and grease seal for application to all types of machinery embodying shafts and particularly electric motors. National Motor Bearing Co., 1173—78th Ave., Oakland, Calif.

Shaftless Motors.—Bulletin 516, 8 pp. Describes various types of shaftless motors; construction, mechanical and electrical characteristics of such motors are outlined as well as their advantages for driving modern production machinery. Engineering data and tables are included. The Louis Allis Co., Milwaukee, Wis.